Essays on Platform Markets

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For my mother. Mojoj majci.

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Abstract

This thesis analyzes regulation, competition and consumer decisions in three distinct platform markets. Chapter 1 studies competition between internet service providers and the interconnection of Content-Delivery-Networks in the light of the net neutrality debate. The results suggest that a departure from a regime of strict net neutrality is associated with efficiency gains. Content-delivery-networks lead to higher incentives for investment on the one hand, however, soften competition for consumers on the other hand. Chapter 2 analyzes competition between ad-based online platforms and platforms' incentives to collect user data. The model predicts a market failure in this type of environment as the level of data collection in the market equilibrium is inefficient. This result provides a justification for privacy regulation as well as competition policy measures, while the market failure can also be counteracted by establishing a market for personal data. Chapter 3 analyzes crowdfunding platforms as a means to collect funds in light of aggregate demand uncertainty. The results suggest that demand in crowdfunding campaigns is strategically withheld in order to counteract future price changes which implies a limited ability of crowdfunding campaigns to reduce demand uncertainty.

Diese Dissertation befasst sich mit Regulierung, Wettbewerb und Konsumentenverhalten in drei unterschiedlichen Plattformmärkten. Kapitel 1 analysiert den Wettbewerb zwischen Netzanbietern und die Zwischenschaltung von Content-Delivery-Networks im Rahmen der Netzneutralitätsdebatte. Die Ergebnisse legen nahe, dass eine Abkehr vom Prinzip der strikten Netzneutralität mit Effizienzgewinnen verbunden ist. Content-Delivery-Networks schaffen dabei einerseits zusätzliche Investitionsanreize für Netzanbieter, andererseits reduzieren sie die Intensität des Wettbewerbs um Endnutzer. Kapitel 2 analysiert den Wettbewerb zwischen werbefinanzierten Online-Plattformen und deren Anreize Nutzerdaten zu sammeln. Die modelltheoretische Analyse legt dar, dass derartige Märkte zu einem Marktversagen neigen, da im Marktgleichgewicht eine ineffiziente Menge an persönlichen Daten gesammelt wird. Dieses Ergebnis rechtfertig Regulierungen im Datenschutzbereich und den Einsatz wettbewerbspolitischer Maßnahmen, wobei dem Marktversagen auch durch die Schaffung eines Marktes für Nutzerdaten entgegengewirkt werden kann. Kapitel 3 analysiert Crowdfunding-Plattformen als Finanzierungsquelle bei unsicherer Gesamtnachfrage. Die Ergebnisse legen nahe, dass die Nachfrage in Crowdfunding-Kampagnen strategisch reduziert wird um künftigen

Preisänderungen entgegenzuwirken. Dies impliziert, dass Crowdfunding-kampagnen nur bedingt geeignet sind um Nachfrageunsicherheit zu reduzieren.

Introduction

This thesis analyzes economic interactions on platform markets, which are commonly defined as markets where an intermediary (the platform) facilitates interaction between distinct market sides.[1] Platforms nowadays span almost every aspect of public and private life, from communications to grocery shopping, and from dating to political decision making. Unsurprisingly, platforms are also subject to a heated debate among politicians and regulators. The business model of Facebook has been heavily criticized after revelations to what extent the company shares user data with third parties. Alphabet, the parent company of Google, has been fined record sums based on antitrust allegations by the European Commission and faces ongoing investigations in the US. The 'net neutrality' debate has led to regulatory changes in the EU and turned into a partisan issue within the US political system. However, one would be misled to think that platforms are restricted to online business models. In fact, the definition only requires the facilitation of interaction between market sides, such that also brick-and-mortar business models can be platform based (e.g. a trade fair matching businesses with clients), infrastructure (e.g. internet service providers connecting content providers to households) or economic institutions in a broader sense (e.g. technological standards encouraging product development for end-users).

The peculiarities of platform markets (direct and indirect network effects, switching costs, potential for natural monopolies, etc.) often challenge standard economic theory and make it difficult to draw implications for policy and regulation. The aim of this thesis is therefore to broaden the understanding of platform markets and to provide insights into mechanisms and dynamics at work. The thesis analyzes three distinct platform markets from the perspective of microeconomic theory. The first chapter considers internet service providers as platforms, providing the infrastructure to connect content providers to consumers. The second chapter considers the role of online media platforms, which attract consumers and advertisers, and obtain revenue by facilitating a match between the two. The third chapter considers crowdfunding platforms which provide a financing source for entrepreneurs by providing access to potential project backers.

[1] The definition roughly follows Rysman (2009). Platform markets are also commonly referred to as being two-sided or multi-sided in their nature, where the sides refer to the distinct market sides which are brought together by the platform. See e.g. Hagiu and Wright (2015) for an alternative definition.

The aim of the first chapter is to contribute on the ongoing debate on 'net neutrality' with a particular focus on the question whether internet service providers should be allowed to offer differentiated service qualities or stick to a single quality level (net neutrality). This regime choice is of particular interest as it affects not only the static efficiency in the market for given network capacities, but also long-term incentives for investment into network infrastructure. The chapter introduces a model of platform competition between internet service providers, where consumers demand heterogeneous online content within two quality regimes: net neutrality and paid prioritization. One key insight is that paid prioritization increases the static efficiency compared to a neutral network. The model also allows for the analysis of paid prioritization intermediated by third-party providers, so-called Content Delivery Networks (CDNs). While the use of CDNs is welfare neutral, it results in higher consumer prices for internet access. Regarding incentives to invest in network capacity, the model suggests that quality differentiation leads to higher investments than a regime of net neutrality, as long as capacity is scarce, while investment is highest in the presence of CDNs.

The second chapter analyzes competition between online platforms whose business model relies on the collection and processing of user data. This is analyzed within a competition framework, where platforms sell targeted advertising (monetary) and collect user data (non-monetary) to improve their targeting capabilities. Considering that users incur privacy costs, the model predicts that the market equilibrium level of data provision is distorted compared to an efficient benchmark and can be too high or too low: if platforms have significant market power, or if targeting benefits are low, too much private data is collected and vice-versa. Further, the results suggest that market power on the user or the advertiser market side leads to more data collection, which implies substitutability between competition policy measures across market sides. Moreover, the model predicts that if platforms engage in two-sided pricing, i.e. monetary transfers on both market sides, data provision is efficient, as it allows to adequately compensate users for their personal data.

Chapter three studies the role of crowdfunding platforms to facilitate the funding and implementation of an investment project. This is analyzed in a two-period setting, where an entrepreneur wants to launch a product, but lacks funding to cover the necessary investment costs. Funds are raised by pre-selling the product in an all-or-nothing crowdfunding campaign in a market of uncertain size (period 1). Observing the outcome of the campaign, the entrepreneur optimizes the pricing of the product and serves the residual demand in a subsequent retail market (period 2). Consumers face a price risk as they want to secure the product at the lowest possible price and are therefore hesitant whether to participate in the crowdfunding campaign in anticipation of future sales. One prediction of the model is that consumers can be incentivized to participate in the crowdfunding by assuring price stability across periods, thereby eliminating the price risk. This is achieved by withholding demand in the crowdfunding period in a way that induces the entrepreneur to not change prices in case of a successful campaign. The characterized equilibrium outcome is consistent with empirical observations and is robust to various changes to the model setup.

Chapter 1

Net Neutrality, Prioritization and the Impact of CDNs

Based on Baake and Sudaric (2018).

1.1 Introduction

This paper contributes to the ongoing debate on ‘net neutrality’ – a concept that broadly requires that all internet traffic should be treated equally (Wu, 2003). One central aspect within the debate revolves around differentiation with respect to Quality-of-Service (QoS), i.e. whether or not all content classes should face identical service quality within the network. While opponents of net neutrality argue that QoS differentiation is part of reasonable network management and should therefore be allowed, if not encouraged, net neutrality proponents argue that this benefits mainly network providers as it opens up new revenue models, and picks a few winners amongst the landscape of content providers (CPs). Indeed this ambivalence can be found e.g. in EU guidelines (EP and Council of the EU, 2015; BEREC, 2016) where a neutral treatment of internet traffic appears as a central pillar of the new regulation, while internet service providers (ISPs) may still offer differentiated QoS under certain conditions.[2] While there are various ways of QoS alterations within the management of a network, we would like to focus on the practice of ‘paid prioritization’ where CPs pay ISPs directly for prioritization of their content. We also consider the impact of Content Delivery Networks (CDNs) such as Akamai or Limelight. Instead of contracting with network operators directly, content providers can contract with an

[2] As long as there is no discrimination within content classes, differentiated QoS measures can be applied to different content classes if they are considered to be ‘reasonable’. While traffic management measures can not be put in place based on purely commercial considerations, the guidelines remain silent on pricing of differentiated QoS in the case they are technologically reasonable. For further details we refer to BEREC (2016).

intermediary, the CDN, which then delivers the traffic to the ISPs.[3]

The purpose of this paper is therefore to analyze how paid prioritization affects, firstly, the static efficiency for a given network infrastructure, and secondly, the dynamic efficiency regarding incentives for investment in network capacity. In a neutral regime ISPs are only allowed to offer one quality level, i.e. all participants experience potential network congestion to the same extent. In a paid prioritization regime ISPs can charge CPs for bypassing the network congestion by having access to a 'priority lane'. In a CDN environment ISPs offer access to their priority lanes to CDNs instead, which then resell the access to CPs. This setup reflects the idea of capacity bottlenecks in the regional or last-mile segment where congestion occurs because of high consumer demand (e.g. in legacy copper or coaxial networks).

We present a two-sided market model where two symmetric ISPs compete for consumers and CPs. Consumers are assumed to single-home, i.e. they purchase internet access only once, while CPs are free to multi-home with respect to their QoS choice. Content is differentiated with respect to connection quality sensitivity and quality levels are derived from a M/M/1 queuing system, where the non-priority quality ('best-effort') always remains free of charge, while the priority quality becomes a possible revenue source.

Using this framework, we show that the two regimes of QoS differentiation are welfare superior to the neutral regime. As content is differentiated, a tiered quality regime allocates priority to highly sensitive content classes, while it leaves content classes with low quality sensitivity in the waiting queue, resulting in a more efficient use of existing network capacity. In particular we show that from a welfare perspective it is irrelevant whether this is achieved by direct paid prioritization or through the use of a CDN. Differences emerge once we take into account strategic effects of the QoS regimes on competition for consumers. Here we argue that QoS differentiation makes the consumer market more elastic leading to lower consumer prices in regimes of QoS differentiation compared to the neutral regime. In particular, under paid prioritization consumer prices are lowest, as here a price increase on the user market has an additional negative effect on the CP market, while this is not the case in a CDN environment. Lastly, we analyze unilateral incentives to increase network capacity from a symmetric equilibrium perspective and show that as long as network capacity is scarce, both discriminatory regimes lead to higher investment in network capacity

[3]CDNs often have direct interconnection points with last-mile networks which can lead to higher traffic quality when delivering content to consumers. However, this quality improvement is not seen as a violation of the principle of net neutrality, as all traffic within the last-mile network is continued to be treated equally, even though from a consumer point of view a quality differentiation takes place. For example, the Netflix-Comcast dispute was not about offering priority lanes for Netflix's services, but rather about Comcast's decision to demand interconnection charges from CDNs with a large amount of outgoing data traffic (caused by Netflix). See for example 'Comcast vs. Netflix: Is this really about Net neutrality?' (Retrieved May 17, 2018 from https://www.cnet.com/news/comcast-vs-netflix-is-this-really-about-net-neutrality).

than the neutral regime, while investment is highest in the CDN case, irrespective of the initial capacity level.

1.2 Related literature

From a modeling perspective we build on the literature on competition in two-sided markets in general and applications in the telecommunications industry in particular. The general setup follows the competitive bottleneck idea in Armstrong (2006) in the sense that we consider single-homing consumers and allow for multi-homing on the CP side. Applications of a two-sided approach to telephone networks (Armstrong, 1998; Laffont et al., 1998a; Laffont et al., 1998b) and to the internet industry (Laffont et al., 2003) can also already be found in earlier work. The key difference is that we explicitly model network congestion and resulting questions of QoS differentiation, while the early stream of literature largely disregards questions of network quality.

This aspect is analyzed in detail in the younger but growing literature on net neutrality.[4] Hermalin and Katz (2007) compare a neutral network where ISPs are restricted to offer a single quality level as opposed to a discriminatory regime where ISPs can offer multiple quality levels to CPs. They conclude with ambiguous welfare effects: offering a single quality level drives some content types out of the market and provides an inefficient low quality level for other content types. However, CPs 'in the middle' are likely to benefit from it. Economides and Hermalin (2012) expand on this result by explicitly modeling bandwidth limits where different qualities could introduce welfare gains in light of congested networks. Following a similar QoS approach, Economides and Hermalin (2015) further show that net neutrality leads to lower investment incentives. Guo and Easley (2016) consider QoS differentiation with respect to effective bandwidth and demonstrate that net neutrality is beneficial for content innovation. Another stream of literature tackles the congestion problem using a queuing approach. Choi and Kim (2010) and Cheng et al. (2011) present a model where a monopoly ISP offers a prioritization service to two CPs. This framework is extended by Krämer and Wiewiorra (2012) to a model with a continuum of heterogeneous CPs. While Choi and Kim (2010) and Cheng et al. (2011) derive mixed results regarding welfare and investment incentives, Krämer and Wiewiorra (2012) show that a discriminatory regime is more efficient and provides higher investment incentives in the long run. While we follow the same direction in terms of CP heterogeneity and the use of queuing, our model differs substantially as we consider platform competition.

This aspect is captured to some extent by Economides and Tåg (2012) and Njoroge et al. (2013) where platform competition is considered but the congestion issue is ignored. Choi et al. (2015) present a closely related model in terms of content

[4] Greenstein et al. (2016) provide an excellent overview over the inherent trade-offs of the net neutrality debate as well as the associated literature.

differentiation and analyze how the business model of CPs affects the optimal price-quality choice of platforms. The key difference is that while we keep the business model fixed in our model, qualities are endogenous in the sense that they are affected by congestion. Secondly, in the case of competition the authors consider cooperative quality choice, while we consider competition in the quality dimension through the platforms' pricing strategies. Kourandi et al. (2015) also consider the case of competing ISPs but focus on the aspect of internet fragmentation when ISPs obtain exclusivity over content. The work most closely related to our model is the paper by Bourreau et al. (2015) where competing ISPs offer queuing based prioritization to differentiated CPs. The main difference from a modeling perspective is how surplus is generated in the economy, as the authors consider an elastic number of CPs and interpret the exclusion of CPs as decrease of content variety. In our model consumers' utility depends on the connection quality of consumed content and not on variety per se. One could therefore see our modeling setup as a combination of the models presented in Choi et al. (2015) and Bourreau et al. (2015). Further, we additionally introduce CDNs as intermediaries which are not considered in any of the previously mentioned papers.

In general the topic of CDNs has largely been disregarded in the net neutrality debate. Hosanagar et al. (2008) study the optimal pricing policy of CDNs but do not perform any welfare comparisons. This is done to some extent in Hau et al. (2011), where different QoS regimes are analyzed in the market for internet interconnection. The overall model differs substantially from ours and in particular the authors do not consider competition between ISPs for consumers, which is a main driver for our results. Interestingly, however, the authors also find that a CDN shifts rents away from consumers to ISPs, a result which qualitatively reoccurs in our analysis, although the underlying mechanics differ. In particular, our results show that CDNs soften competition for consumers compared to a regime where CPs directly contract with ISPs.

Our analysis supports the results obtained by Krämer and Wiewiorra (2012) and Bourreau et al. (2015): a discriminatory regime is superior in terms of static efficiency and tends to provide higher investment in network capacity. At the same time our work complements the existing literature in terms of the role of CDNs. While total efficiency is identical to paid prioritization, consumers face higher prices when CDNs are used. Regarding the ongoing debate on net neutrality our results therefore suggest that if QoS differentiation is to be allowed (see e.g. recent advances in the US), direct prioritization agreements between CPs and ISPs should be preferred over the indirect contracting via CDNs from a (static) consumer perspective, as they lead to lower consumer prices, while investment in network infrastructure is highest in the presence of CDNs.

1.3 Model

We study different QoS regimes in a two-sided market setting where ISPs deliver content from CPs on one market side to consumers on the other market side. CPs strike QoS deals either with ISPs directly (section 1.4.1 and 1.4.2) or with a CDN in section 1.4.3.

Internet service providers There are two identical ISPs $i = 1, 2$ located at the ends of a Hotelling line (location $\lambda_i = 0$ for $i = 1$ and $\lambda_i = 1$ for $i = 2$). ISPs sell internet access to consumers at price p_i and make QoS offers (f_i, q_i) to CPs, such that in exchange for a fee f_i consumers in network i can be reached at quality q_i. In the case of net neutrality the only offer ISPs can make is of the form $(0, q_i^n)$ where q_i^n denotes the best-effort quality in network i, which is free of charge. This reflects the idea that there is ubiquitous interconnectivity in the economy such that CPs can reach consumers of network i irrespective of whether there is an existing agreement with the network. Under paid prioritization ISPs can offer in addition to the free best-effort quality a prioritization service (f_i, q_i^p) with $f_i \geq 0$ where q_i^p denotes the priority quality level in network i.

The quality levels q_i^n and q_i^p are derived from a M/M/1 queuing model with an arrival rate of content requests equal to one such that waiting times are given by

$$w_i^p = \frac{1}{k_i - N_i Y_i} \text{ with prioritization,} \tag{1.1}$$

$$w_i^n = \frac{k_i}{k_i - N_i} w_i^p \text{ without prioritization,} \tag{1.2}$$

where $N_i \in [0, 1]$ denotes the mass of consumers connected to ISP i, $Y_i \in [0, 1]$ denotes the mass of CPs who purchased prioritization in network i, and k_i is the network capacity of ISP i. Quality levels in network i are then defined as

$$q_i^p = 1 - w_i^p \text{ with prioritization,} \tag{1.3}$$

$$q_i^n = 1 - w_i^n \text{ without prioritization.} \tag{1.4}$$

Further, we make the following assumption regarding network capacities such that quality levels remain non-negative.

Assumption 1.1 *Network capacities are sufficiently large $k_i \in (2, \infty)$.*

This assumption ensures that waiting times do not explode for low capacity levels such that we have $w_i^p, w_i^n \in (0, 1)$ and therefore $q_i^p, q_i^n \in (0, 1)$. Also, this assumption implies that each network could shoulder the whole traffic by itself such that there are not any purely allocative reasons behind our setup. Also note that $q_i^p > q_i^n$ and $\lim_{k_i \to \infty}(q_i^p - q_i^n) = 0$, i.e. if capacities are large waiting times in all queues converge to zero and quality differences disappear.

Content providers There is a continuum of differentiated CPs with total mass normalized to one. CPs are differentiated with respect to their quality sensitivity $\theta \in \Theta \equiv [0,1]$ which we assume to be uniformly distributed. Low values of θ correspond to content-types with low sensitivity with respect to transmission quality (e.g. e-mails) whereas high values represent quality-sensitive services (e.g. live streaming).

We assume the CPs' business model is entirely passive (e.g. ad-based) and that the delivery of content of type θ at quality level q to one consumer generates advertisement revenues $r(\theta, q) = \theta q$ such that θ measures the importance of quality for the revenue generation. A CP of type θ decides whether to purchase prioritization ($h_i^\theta = p$) in network i or not ($h_i^\theta = n$) such that profits obtained from network i are given by

$$\pi_i(\theta, h_i^\theta) = \begin{cases} r(\theta, q_i^n)N_i & \text{if } h_i^\theta = n \\ r(\theta, q_i^p)N_i - f_i & \text{if } h_i^\theta = p \end{cases} \tag{1.5}$$

resulting in total profits of a CP of type θ with QoS plan $h^\theta = \{h_1^\theta, h_2^\theta\}$ of

$$\pi(\theta, h^\theta) = \sum_{i \in \{1,2\}} \pi_i(\theta, h_i^\theta). \tag{1.6}$$

We can then define $\mathcal{P}_i = \{\theta \in \Theta \mid h_i^\theta = p\}$ as the set of content types prioritizing in network i and $Y_i = \int_{\theta \in \mathcal{P}_i} d\theta$ as the total mass of prioritized content in network i.

Consumers There is a continuum of differentiated consumers with total mass normalized to one. Consumers have a uniformly distributed location $x \in [0,1]$ and obtain utility $v(\theta, q) = \theta q$ from consuming one unit of content from a CP of type θ delivered with quality q.[5] The total utility V_i from content consumption in network i is then given by

$$V_i = \int_{\theta \notin \mathcal{P}_i} v(\theta, q_i^n) d\theta + \int_{\theta \in \mathcal{P}_i} v(\theta, q_i^p) d\theta \tag{1.7}$$

and can be thought of as a summary statistic for the network quality of ISP i. Overall utility $u_i(x)$ from connecting to network i is then given by

$$u_i(x) = \underline{u} + V_i - p_i - |\lambda_i - x| \tag{1.8}$$

and depends on the aggregate utility from content consumption V_i, the internet access price p_i and the location of the consumer.[6] Lastly, $\underline{u}$ captures utility which is derived from connecting to the internet but not covered by our CP model and is assumed to be sufficiently high such that market coverage is ensured.

[5] Note, in our model $v(\theta, q) = r(\theta, q)$ which is a simplifying assumption. We could also allow for a setting where consumers receive a fraction s of the surplus θq_i and CPs the remaining fraction $(1 - s)$. Our results would not change qualitatively.

[6] We omit the arguments of V_i where it does not lead to confusion.

Timing In a first step, ISPs set consumer prices p_i and (if allowed) prioritization fees f_i. Secondly, consumers decide which network to join and CPs decide in which network to purchase prioritization (if applicable) simultaneously. The solution concept is sub-game perfection.

1.4 Equilibrium analysis

In this section we present equilibrium outcomes for the three different QoS regimes which we will refer to by the superscripts given in brackets: Net neutrality (n), paid prioritization (p) and Content Delivery Networks (c). Details of the formal analysis are delegated to Appendix 1.A.1 and proofs can be found in Appendix 1.A.2.

1.4.1 Net neutrality

In this section we consider the benchmark scenario of net neutrality. In this scenario ISPs can not sell prioritization and their only source of revenue is selling internet access to consumers, i.e. we have $\mathcal{P}_i = \emptyset$ and therefore $Y_i = 0$ in both networks. As the best-effort quality level is free of charge, CPs will reach consumers of network i at quality level q_i^n such that we have $h^\theta = (n, n) \; \forall \; \theta$. Total profits from content delivery obtained by a CP of type θ are then given by

$$\pi(\theta, h^\theta) = \theta \left(q_1^n N_1 + q_2^n N_2 \right) \tag{1.9}$$

with $q_i^n = 1 - 1/(k_i - N_i)$ for $i = \{1, 2\}$. Turning to consumers the aggregate utility from content consumption without prioritization V_i is then given by

$$V_i = q_i^n \int_0^1 \theta d\theta. \tag{1.10}$$

Since there is only one quality level in the neutral regime all content types arrive at the uniform quality level q^n. The consumer market shares of both ISPs are then given by the indifferent consumer $\hat{x} : u_1(\hat{x}) = u_2(\hat{x})$ on the Hotelling line.

$$N_1 = \hat{x} \equiv \frac{1}{2} + \frac{1}{2} \left[(V_1 - p_1) - (V_2 - p_2) \right] \text{ and } N_2 = 1 - \hat{x}. \tag{1.11}$$

Note, that (1.11) defines N_i only implicitly as the quality levels q_i^n also depend on the consumer market shares. We therefore make use of the implicit function theorem to obtain market share reactions $\partial N_i / \partial p_i$. Details can be found in Appendix 1.A.1. The first order conditions to the ISPs' maximization problems

$$\max_{p_i} \Pi_i = p_i N_i \tag{1.12}$$

can then be written using the market share reactions obtained in (1.34) such that we get

$$p_i = \frac{N_i}{-\partial N_i / \partial p_i}. \tag{1.13}$$

Note, that even though this is a very simple maximization problem it is not the standard Hotelling problem. The endogeneity of q_i^n leads to less elastic market shares N_i. Utilizing symmetry in network capacities $k_i = k_j = k$ we obtain the unique symmetric solution p^n satisfying $p^n = \arg\max_{p_i} \Pi_i|_{p_j=p^n}$ where

$$p^n = \underbrace{1 + \frac{2}{(2k-1)^2}}_{=-N_i/(\partial N_i/\partial p_i)}. \tag{1.14}$$

Equilibrium market shares are then given by $N_i = N_j = 1/2$. Regarding comparative statics we see that $\partial p^n / \partial k < 0$, i.e. consumer prices are lower for higher (symmetric) capacity levels. The reason is that higher capacity levels make consumer demand more elastic $\partial^2 N_i / \partial p_i \partial k < 0$. Consider the case where k is very large. Then congestion is basically irrelevant and quality levels in both networks effectively do not depend on the ISPs' market shares, such that ISPs only compete in prices. If capacity is scarce the congestion problem dampens consumers willingness to switch networks as by joining the rival network the rival's quality decreases. Hence, demand is less elastic and consumer prices increase. The property $\partial p^n / \partial k < 0$ will reoccur throughout the analysis and we will refer to it as 'capacity effect'.

1.4.2 Paid prioritization

In this section we consider the case where ISPs directly offer CPs paid prioritization agreements. The proposed offer consists of content delivery to all consumers in network i at priority quality q_i^p in exchange for a fee f_i, while content delivery at the best-effort quality level q_i^n remains free of charge.[7]

CPs make the decision whether to purchase prioritization for each network separately. The decision depends on how the profit of reaching consumers connected to ISP i at best-effort quality q_i^n compares to the profit under a prioritization agreement with access to the priority quality q_i^p. By comparing the profit levels given in (1.5) we can pin down an indifferent CP of type $\hat{\theta}_i$ such that $\pi_i(\hat{\theta}_i, n) = \pi_i(\hat{\theta}_i, p)$ with

$$\hat{\theta}_i = \frac{f_i}{(q_i^p - q_i^n) N_i}. \tag{1.15}$$

[7] As we consider unit demand the distinction between a linear per-consumer fee and a lump-sum fee to reach all consumers in network i is irrelevant. We stick to the latter specification for reasons of conciseness.

CPs will therefore engage in a prioritization contract if they offer sufficiently quality-sensitive content $\theta \geq \hat{\theta}_i$, and stick to the best-effort quality if their content type is insensitive $\theta < \hat{\theta}_i$. The set of prioritizing CPs in network i is then given by $\mathcal{P}_i = [\hat{\theta}_i, 1]$ such that the mass of prioritized traffic in network i is given by $Y_i = 1 - \hat{\theta}_i$. Turning to consumers the aggregate utility from content consumption V_i under prioritization is given by

$$V_i = q_i^n \int_0^{\hat{\theta}_i} \theta d\theta + q_i^p \int_{\hat{\theta}_i}^1 \theta d\theta \tag{1.16}$$

and consists of prioritized ($\theta \geq \hat{\theta}_i$) and non-prioritized ($\theta < \hat{\theta}_i$) content. The consumers' decision which network to join is given as in (1.11) by pinning down an indifferent consumer. The profit maximization problem of an ISP can then be written as

$$\max_{p_i, f_i} \Pi_i = p_i N_i + f_i Y_i. \tag{1.17}$$

Due to the endogeneity of the quality levels, we again apply the implicit function theorem to obtain consumer market share reactions $\partial N_i/\partial p_j, \partial N_i/\partial f_j$ and CP share reactions $\partial Y_i/\partial p_j, \partial Y_i/\partial f_j$ for $i, j = \{1, 2\}$.[8] Further we introduce the following intermediary result which provides us assurance of an interior solution to the maximization problem.

Lemma 1.1 *Each ISP has an incentive to offer prioritization.*

Proof. See Appendix. □

First, prioritization introduces additional revenue streams on the CP side of the market. Secondly, compared to no prioritization the network's overall quality V_i increases as some highly sensitive content types now arrive at high quality, while the quality of the remaining content types barely changes. This pushes more consumers into the network offering prioritization which increases the ISP's profit even further. As this argument holds for each ISP irrespective of whether the other ISP offers prioritization or not, offering prioritization is a strictly dominant strategy. Given Lemma 1.1 we can now focus on the interior solution given by the first order conditions to the maximization problem in (1.17) such that

$$p_i = \frac{N_i}{-\partial N_i/\partial p_i} - f_i \frac{\partial Y_i/\partial p_i}{\partial N_i/\partial p_i} \text{ and } f_i = \frac{Y_i}{-\partial Y_i/\partial f_i} - p_i \frac{\partial N_i/\partial f_i}{\partial Y_i/\partial f_i}. \tag{1.18}$$

Comparing (1.18) to (1.13) we see that optimal consumer price setting now takes into account the effect on the CP market, where an increase in prices reduces the number of consumers and hence reduces the revenue from the prioritization business as it decreases the share of prioritizing CPs. Going back to the definition of the indifferent content class in (1.15) we see that there are two effects affecting the

[8] Details can be found in Appendix 1.A.1.

share of prioritizing CPs. First, there is a direct effect when increasing consumer prices, as the share of consumers N_i decreases. Secondly, the indifferent content class depends on the difference in quality levels $q_i^p - q_i^n$. As a reduction in the number of consumers reduces the total traffic in the network and hence the congestion problem, the difference in quality levels decreases when the number of consumers goes down, pushing the indifferent content class upwards and hence reducing the share of prioritizing CPs.[9] In summary, introducing prioritization therefore restricts the ability of ISPs to raise consumer prices.

The optimal prioritization fee similarly balances the revenue generation across both market sides. While an increase in fees reduces the share of prioritizing CPs, the effect on the consumer market is not necessarily monotone. Coming from a situation of no prioritization, a higher share of prioritized content increases utility from content consumption as quality sensitive content arrives at high quality. However, if the share of prioritized content is too large, the congestion externality imposed on the priority queue might outweigh the benefits of prioritizing additional content classes which would decrease overall network quality.

Continuing with the analysis we find a symmetric equilibrium such that $(p^p, f^p) = \arg\max_{p_i, f_i} \Pi_i|_{p_j = p^p, f_j = f^p}$ resulting in $Y_i = Y_j = Y^p \equiv 1 - \hat{\theta}^p = 2k - \psi$ and $N_i = N_j = 1/2$ as well as $\partial N_i / \partial f_i = 0$ for $i \neq j$ with equilibrium values

$$p^p = 5 - \underbrace{\frac{(8k-6)\psi}{(2k-1)^2}}_{= \frac{N_i}{-\partial N_i / \partial p_i}} - f^p \underbrace{\frac{4k}{(2k-1)}}_{= \frac{\partial Y_i / \partial p_i}{\partial N_i / \partial p_i}} \text{ and } f^p = Y^p \underbrace{\frac{1}{2k(2k-1)}}_{= \frac{1}{-\partial Y_i / \partial f_i}} \tag{1.19}$$

where $\psi := \sqrt{2k(2k-1)}$. Note that $\partial Y^p / \partial k < 0$ (or equivalently $\partial \hat{\theta}^p / \partial k > 0$), i.e. the higher the capacity level in the market the lower share of prioritized content classes. If capacity levels rise, networks become less congested and the quality gain from prioritization decreases.[10] Therefore, only CPs with extremely sensitive content types opt for prioritization. Regarding consumer prices we obtain $\partial p^p / \partial k < 0$ which is in line with the capacity effect described in section 1.4.1. The effect of the quality level on prioritization fees is given by $\partial f^p / \partial k < 0$ which reflects the decreasing advantage of prioritization if overall capacity is large. Further, this effect prevails even in presence of an increased elasticity on the consumer market such that standard platform logic would predict a price increase on the CP market side.

Note that from equations (1.14) and (1.19) we can infer the equilibrium market share elasticity $\partial N_i / \partial p_i$ in both regimes. Comparing the two cases we see that the consumers' reaction to price changes is stronger in a prioritization regime.[11] The reason for this is that introducing a priority queue already eases the congestion

[9] It is easy to verify that $\partial(q_i^p - q_i^n)/\partial N_i > 0$.
[10] To see this remember that $\lim_{k \to \infty}(q_i^p - q_i^n) = 0$.
[11] The comparison boils down to $\psi > 2(2k-1)^2/(4k-3)$ which is satisfied under Assumption 1.1.

problem in the networks. Therefore by switching to the rival network the overall network quality decreases less, hence market shares are more elastic in a prioritization regime. We will refer to this effect simply as ‘elasticity effect’. Note this effect is very similar to the capacity effect described in section 1.4.1. However, while the capacity effect states that market shares become more elastic when the capacity level k increases, the elasticity effect states that for a given level of k market shares are more elastic in a prioritization regime.

Lastly, we get $\partial N_i/\partial f_i = 0$ in equilibrium. To gain intuition for this result consider the case where coming from a neutral regime (f_i prohibitively high) the prioritization fee is reduced such that $Y_i > 0$. This increases the revenue on the CP side and at the same time increases the network's quality which attracts more consumers. This ‘double benefit’ is exploited fully in equilibrium, resulting in $\partial N_i/\partial f_i = 0$.

1.4.3 Content Delivery Networks

In this section we consider an alteration to the prioritization setup presented in section 1.4.2. In particular we introduce a Content Delivery Network (CDN) as an additional player which serves as an intermediary between CPs and ISPs. The idea is that the CDN enters an agreement with ISPs such that traffic coming from the CDN is prioritized, while traffic not coming from the CDN remains unprioritized.[12]

For this we introduce an additional ‘offer stage’ at the beginning of the game. In the offer stage the CDN publicly announces lump-sum transfers $F_i \in \mathbb{R}$, which the ISPs can either accept or reject.[13] If ISP i accepts offer F_i, the CDN is free to set the prioritization fee f_i for reaching costumers in network i just like in section 1.4.2 while ISP i only sets consumer prices p_i. If ISP i rejects offer F_i, prioritization in network i is offered by ISP i instead.[14] In any case prices p_i, p_j and prioritization fees f_i, f_j are set simultaneously as before. This setting resembles the industry practice, where ISPs and CDNs make long-term infrastructure level decisions, while offers made to consumers and CPs are made once those decisions are made.[15]

To avoid multiplicity of equilibria we apply the payoff dominance refinement (Harsanyi and Selten, 1988) to the coordination game in the offer stage, such that in case there

[12]For simplicity reasons we abstract from any additional quality improvements due to the use of CDNs.

[13]One can alternatively consider a two-part tariff $T_i = (t_i, F_i) \in \mathbb{R}^2$ where t_i is an additional linear fee. It is clear that t_i introduces a double marginalization inefficiency which would reduce the total obtainable profit of the CDN. We therefore restrict our analysis to the case of $t_i = 0$ which reduces the proposal to the lump-sum fee F_i.

[14]We implicitly assume that ISPs commit to not offer prioritization themselves in case they accept the offer such that the offer F_i can be seen as an exclusive dealing arrangement. Without commitment the standard Bertrand argument would apply, as in particular the CDN would undercut any positive fee set by the ISP.

[15]The fact that offers F_i are public is a simplifying assumption which allows us to focus on the induced change in competition dynamics. If we consider private offers instead, existence of the presented equilibrium remains unchanged.

are multiple equilibria when deciding whether to accept offers F_i, we select the Pareto-dominant equilibrium in terms of ISP profits.

Suppose both offers have been accepted. The maximization problem of the CDN is then given by

$$\max_{f_i,f_j} \Pi_c = f_iY_i + f_jY_j - F_i - F_j,\ i \neq j \tag{1.20}$$

where Y_i and Y_j are obtained as in section 1.4.2 and F_i, F_j denote (sunk) lump-sum transfers to both ISP i and j. ISPs in this case only compete on the consumer market:

$$\max_{p_i} \Pi_i = p_iN_i + F_i,\ i = 1, 2. \tag{1.21}$$

Market share reactions $\partial N_i/\partial p_j, \partial N_i/\partial f_j$ as well as $\partial Y_i/\partial p_j, \partial Y_i/\partial f_j$ for $i, j = \{1, 2\}$ are again obtained as in (1.36) giving rise to first order conditions to maximization problems (1.20) and (1.21) of:

$$p_i = \frac{N_i}{-\partial N_i/\partial p_i} \text{ and } f_i = \frac{Y_i}{-\partial Y_i/\partial f_i} - f_j\frac{\partial Y_j/\partial f_i}{\partial Y_i/\partial f_i},\ i \neq j. \tag{1.22}$$

We can immediately see that the maximization problem of the ISPs now closely resembles the maximization problem under the neutral regime. In particular ISPs now do not internalize the negative effect of a price increase on the share of prioritized content as they did in section 1.4.2. However, remember that there is a tiered queue on the content market, such that the market share reaction differs compared to the neutral regime due to the elasticity effect. The CDN, on the other hand, internalizes the effect of a fee setting in market i on the share of prioritized content in network j, while in section 1.4.2 the fee setting internalized the effect on the consumer market share in network i.

Continuing with the analysis we again obtain a symmetric equilibrium $(f^c, f^c) = \arg\max_{f_i,f_j} \Pi_c|_{p_i=p_j=p^c}$ and $p^c = \arg\max_{p_i} \Pi_i|_{f_i=f_j=f^c,p_j=p^c}$ for $i \neq j$ resulting in $N_i = N_j = 1/2$ and $Y_i = Y_j = Y^c \equiv 1 - \hat{\theta}^c = 2k - \psi$ and $\partial Y_j/\partial f_i = 0$. Equilibrium values are given by

$$p^c = \underbrace{5 - \frac{(8k-6)\psi}{(2k-1)^2}}_{=\frac{N_i}{-\partial N_i/\partial p_i}} \text{ and } f^c = Y^c \underbrace{\frac{1}{2k(2k-1)}}_{=\frac{1}{-\partial Y_i/\partial f_i}} \tag{1.23}$$

and $\psi = \sqrt{2k(2k-1)}$ as in section 1.4.2. It now remains to show that this sub-game is actually reached, i.e. the CDN makes offers which are accepted by the ISPs.

Lemma 1.2 *The optimal offer is symmetric $F_i = F_j = F^c$ and is accepted by both ISPs in equilibrium.*

Proof. See Appendix. □

Given Lemma 1.2 we know that the CDN prefers contracting with both ISPs compared to contracting with only one ISP. Further, the proposed offers are accepted by the ISPs such that the presented equilibrium outcome is indeed sub-game perfect which allows us to compare derived equilibrium values to the previous QoS regimes. We immediately see that $f^c = f^p$ and $Y^c = Y^p$ while $p^c \neq p^p$ which gives rise to the following result.

Proposition 1.1 *The use of CDNs is welfare-equivalent to paid prioritization.*

Proof. See Appendix. □

Proposition 1.1 implies that from a total welfare perspective it is irrelevant whether prioritization is achieved by direct paid prioritization offers made by ISPs, or whether prioritization is offered through the use of a CDN. In particular the CDN will pick prioritization fees which are equivalent to the paid prioritization scenario, resulting in an identical share of prioritized content classes.

Going back to the definition of the critical content class in (1.15), we can see that the only effect f_i has on Y_j is via the consumer market share N_j. Now consider the case of f_i, f_j being large such that $Y_i = Y_j = 0$ and start decreasing f_i such that we obtain $Y_i > 0$. This increases the network quality V_i in network i and hence pulls consumers from network i into network j, increasing the revenue obtained from network i. Now consider a decrease in f_j such that $Y_j > 0$. Consumers are pulled away from network i into network j, decreasing the revenue obtained from network i and increasing the revenue obtained from network j. Given these 'push-and-pull' effects, it is optimal for the CDN to set its prioritization fees such that the marginal effect on the consumer market vanishes, resulting in $\partial N_i / \partial f_i = 0$ and thus $\partial Y_j / \partial f_i = 0$, which in turn leads to identical equilibrium fees as in section 1.4.2.

We can also immediately see that $p^c > p^p$ as the optimal consumer prices now do not take into account the adverse revenue effect on the CP side $\partial Y_i / \partial p_i$ as is the case under paid prioritization. Unsurprisingly, we therefore observe higher consumer prices in the CDN case. As we consider a covered consumer market the total welfare is unaffected by this price increase, resulting in Proposition 1.1.

1.5 Comparison

This section compares the different QoS regimes from section 1.4. In the first part we look at profits and consumer surplus separately to gain a better understanding of the underlying dynamics before combining our results in a single welfare measure. The second part compares incentives to invest in network capacities.

1.5.1 Welfare

We start this section by defining simplified surplus metrics for symmetric equilibrium outcomes. First, remember that in our symmetric outcomes $N_i = N_j = 1/2$ while the share of prioritized content is pinned down by an indifferent content class $\hat{\theta}$ such that the share of prioritized content takes the form $Y_i = Y_j = Y = 1 - \hat{\theta}$. It turns out to be helpful to denote equilibrium quality levels as functions of $\hat{\theta}$ such that we have $q_i^n = q_j^n = q^n(\hat{\theta}), q_i^p = q_j^p = q^p(\hat{\theta})$. Note, that in a regime of net neutrality we have $Y = 0$ or equivalently $\hat{\theta} = \hat{\theta}^n := 1$. Starting with the definition of consumer utility (1.8) we can then denote consumer surplus S_C as a function of symmetric consumer prices p and a cutoff level $\hat{\theta}$:

$$S_C(p, \hat{\theta}) = 2\int_0^{1/2} u_i(x)dx = \underline{u} + V(\hat{\theta}) - p - \frac{1}{4} \tag{1.24}$$

where

$$V(\hat{\theta}) = q^n(\hat{\theta}) \int_0^{\hat{\theta}} \theta d\theta + q^p(\hat{\theta}) \int_{\hat{\theta}}^1 \theta d\theta. \tag{1.25}$$

Similarly, we can define total CP industry profits S_{CP} as a function of a cutoff content class $\hat{\theta}$ and a symmetric prioritization fee f in the case of prioritization.[16]

$$S_{CP}(f, \hat{\theta}) = \begin{cases} V(\hat{\theta}) - 2f(1-\hat{\theta}) & \text{for } \hat{\theta} < 1 \\ V(\hat{\theta}) & \text{for } \hat{\theta} = 1 \end{cases} \tag{1.26}$$

Finally, we can define total ISP (incl. CDN in section 1.4.3) industry profits S_{ISP} as a function of prices p, f and critical content class $\hat{\theta}$.

$$S_{ISP}(p, f, \hat{\theta}) = \begin{cases} p + 2f(1-\hat{\theta}) & \text{for } \hat{\theta} < 1 \\ p & \text{for } \hat{\theta} = 1 \end{cases} \tag{1.27}$$

Combining all three measures into a total surplus measure TS we obtain

$$TS(\hat{\theta}) = S_C + S_{CP} + S_{ISP} = \underline{u} + 2V(\hat{\theta}) - \frac{1}{4}. \tag{1.28}$$

We immediately see that the network quality $V(\hat{\theta})$ plays a central role and we therefore introduce the following intermediate result which will become useful when we compare the different QoS regimes.

[16] In a prioritization regime CP industry profits are given by $S_{CP}(f, \hat{\theta}) = \int_0^{\hat{\theta}} \pi(\theta, (n,n))\, d\theta + \int_{\hat{\theta}}^1 \pi(\theta, (p,p))\, d\theta = \int_0^{\hat{\theta}} 2r\left(q^n(\hat{\theta}), \theta\right) d\theta + \int_{\hat{\theta}}^1 2\left(r\left(q^p(\hat{\theta}), \theta\right) - f\right) d\theta = V(\hat{\theta}) - 2f(1-\hat{\theta})$ while in the neutral regime we have $S_{CP}(\emptyset, 1) = \int_0^1 \pi(\theta, (n,n))\, d\theta = \int_0^1 2r\left(q^n(1), \theta\right) d\theta = V(1)$.

Lemma 1.3 *The network quality $V(\hat{\theta})$ is higher in a prioritization regime:*

$$V(1) < V(\hat{\theta}),\ \hat{\theta} \in (0,1)$$

Proof. See Appendix. □

To gain intuition for Lemma 1.3 it is helpful to consider the extreme case $\hat{\theta} = 1$, i.e. no prioritization and all traffic taking place in the best-effort queue. Marginally decreasing $\hat{\theta}$ then implies that highly quality-sensitive content arrives at priority quality, while the quality for all the remaining traffic remains effectively unchanged, i.e. overall network quality increases. A similar argument can be made for the other extreme case $\hat{\theta} = 0$, where all content is 'prioritized', i.e. again the entire traffic takes place in a single quality queue, while for intermediate levels $\hat{\theta} \in (0,1)$ content distributes across both queues and some sensitive content classes arrive at priority quality. Hence $V(\hat{\theta})$ is high for intermediate levels of $\hat{\theta}$. Starting with consumers we then obtain the following result by comparing consumer surplus under the different QoS regimes.

Proposition 1.2 *Consumers benefit from prioritization as consumer prices decline and network quality increases. In particular we have:*

i.) $V(\hat{\theta}^p) = V(\hat{\theta}^c) > V(\hat{\theta}^n)$

ii.) $p^n > p^c > p^p$

iii.) $S_C(p^p, \hat{\theta}^p) > S_C(p^c, \hat{\theta}^c) > S_C(p^n, \hat{\theta}^n)$

Proof. See Appendix. □

Prioritization has two main benefits for consumers. First, it allocates existing capacity more efficiently such that highly quality sensitive content arrives at priority quality, while content classes for which transmission quality plays a minor role are put in a waiting queue. This increases the total utility from content consumption. Secondly, prioritization makes it harder for ISPs to raise consumer prices as the consumer market becomes more elastic, and since losing consumers to the rival network has an additional negative effect on the revenue obtained on the CP market side. The last effect is not present in the case of CDNs as here ISPs do not internalize the negative effect on the CP side. However, in both cases consumers benefit from prioritization. Turning to the content industry, the following proposition summarizes the main finding.

Proposition 1.3 *The content industry does not benefit from prioritization.*

$$S_{CP}(f^n, \hat{\theta}^n) > S_{CP}(f^p, \hat{\theta}^p) = S_{CP}(f^c, \hat{\theta}^c)$$

Proof. See Appendix. □

There are two main reasons why the content industry does not profit from prioritization. For content classes which are not prioritized $\theta < \hat{\theta}$, the free best-effort quality decreases as we have $\partial q^n(\hat{\theta})/\partial\hat{\theta} > 0$, resulting in lower profits for CPs with low quality sensitivity. CPs who purchased prioritization now have their content delivered at higher quality, however, the content delivery is no longer free of charge. The content class which is indifferent between prioritization and best-effort quality $\hat{\theta}$ is worse off under prioritization, as the best-effort quality decreases compared to a neutral regime. Only those CPs with very high quality sensitivity potentially benefit from prioritization. However, in total the content industry is worse off under prioritization. When it comes to the comparison between a paid prioritization regime and a CDN based model this result predicts that CPs are indifferent between the two as the outcome is equivalent.

Proposition 1.4 *ISPs do not benefit from prioritization.*

$$S_{ISP}(p^n, f^n, \hat{\theta}^n) > S_{ISP}(p^c, f^c, \hat{\theta}^c) > S_{ISP}(p^p, f^p, \hat{\theta}^p) \tag{1.29}$$

Proof. See Appendix. □

Even though prioritization opens up new revenue streams on the CP side, the induced competition dynamics on the consumer market lead to lower industry profits. Consumer prices decrease as the consumer market becomes more elastic and losing consumers now has additional negative effects on the CP side of the business. This reduction in revenue outweighs any additional revenue which can be obtained from selling prioritization to CPs, resulting in lower ISP industry profits under prioritization. In the case of CDNs the ability to raise consumer prices is less restricted compared to the paid prioritization case, resulting in higher industry profits in the presence of CDNs compared to paid prioritization. However, ISPs would be better off if they would not introduce prioritization offers even if they would be allowed to do so.

Corollary 1.1 *ISPs face a prisoner's dilemma when deciding whether to offer prioritization.*

Proof. Follows from Lemma 1.1 and Proposition 1.4. □

As ISPs have an unilateral incentive to introduce prioritization offers (see Lemma 1.1), they end up in a situation where competition for consumers is strengthened to such an extent, that the negative effect on the consumer market outweighs the additional revenues made on the CP market side. This result supports the finding in Bourreau et al. (2015). Delegating the prioritization business to a CDN can then be seen as a remedy to soften competition on the consumer market.

Proposition 1.5 *Welfare is higher under prioritization*

$$TS(\hat{\theta}^p) = TS(\hat{\theta}^c) > TS(\hat{\theta}^n)$$

Proof. Follows from Lemma 1.3. □

As prices are transfers from consumers to ISPs, and fees from CPs to ISPs / CDN, the welfare comparison boils down to the aggregate network quality. Under a prioritization regime the existing network capacity is allocated more efficiently, resulting in a higher total surplus.

1.5.2 Investment incentives

In this section we want to shed light on how the different QoS regimes affect investment in network infrastructure. For this we compare investment incentives from a symmetric equilibrium perspective. The idea is that capacity investments are typically long-term decisions such that the industry is in equilibrium before the next investment decisions are made. We assume that investment costs for capacity expansion are identical in all regimes and therefore restrict our analysis to the comparison of marginal profits gross of investment costs. The changes of p_i, f_i, N_i and Y_i with respect to k_i are again obtained by applying the implicit function theorem, while we evaluate all expressions at respective equilibrium values which allows us to make use of the envelope theorem for simplification. Detailed derivations can be found in Appendix 1.A.1.

Starting with the neutral regime we obtain

$$\frac{d\Pi_i}{dk_i} = p_i \overbrace{\left(\underbrace{\frac{\partial N_i}{\partial k_i}}_{+} + \underbrace{\frac{\partial N_i}{\partial p_j}}_{+} \underbrace{\frac{\partial p_j}{\partial k_i}}_{-} \right)}^{\text{Consumer effect}} > 0. \tag{1.30}$$

The marginal profit of capacity investment mainly depends on the direct effect $\partial N_i / \partial k_i > 0$ of investment in network quality and thereby attracting consumers, and the strategic effect $\partial p_j / \partial k_i < 0$ of network j in order to recapture lost market share by decreasing prices. The former effect outweighs the latter, such that the overall effect is positive, and we will refer to the overall effect simply as ‘consumer effect’.

Turning to the paid prioritization case we obtain investment incentives of

$$\frac{d\Pi_i}{dk_i} = \overbrace{p_i\left(\underbrace{\frac{\partial N_i}{\partial k_i}}_{+} + \underbrace{\frac{\partial N_i}{\partial p_j}}_{+}\underbrace{\frac{\partial p_j}{\partial k_i}}_{-}\right)}^{\text{Consumer effect}} + \overbrace{f_i\left(\underbrace{\frac{\partial Y_i}{\partial k_i}}_{-} + \underbrace{\frac{\partial Y_i}{\partial p_j}}_{+}\underbrace{\frac{\partial p_j}{\partial k_i}}_{-}\right)}^{\text{CP effect}} > 0. \tag{1.31}$$

The dynamics behind the consumer effect are identical as in the neutral regime but differ in magnitude (see detailed discussion below). The main difference is that we now have an additional effect on the CP market side which we will refer to as 'CP effect'. We again distinguish two different sub-effects: A direct effect $\partial Y_i/\partial k_i < 0$ and a strategic effect $\partial p_j/\partial k_i < 0$. As a capacity increase eases the congestion problem, less CPs opt for prioritization, resulting in a negative direct effect. Similar to the consumer effect, network j reacts by lowering consumer prices, reducing the market share of network i and thereby making prioritization in network i even less attractive, resulting in a second negative (strategic) effect. As the business model of prioritization relies on a congestion problem, investment in capacity expansion directly reduces the obtainable profit from the CP side of the market. In total the positive consumer effect, however, outweighs the negative CP effect, resulting in positive investment incentives.

For the CDN case we need to take into account the effect of the investment decision on the business relationship with the CDN. It turns out to be helpful to denote the lump-sum transfer F^c as a fraction $\alpha \in [0,1]$ of the CDN profit where $\alpha := F^c/\Pi_c$. The investment incentive of an ISP can then be written as $d\tilde{\Pi}_i/dk_i$ where $\tilde{\Pi}_i := \Pi_i + \alpha\Pi_c$ such that $d\tilde{\Pi}_i/dk_i$ is given by

$$\frac{d\tilde{\Pi}_i}{dk_i} = \overbrace{p_i\left(\underbrace{\frac{\partial N_i}{\partial k_i}}_{+} + \underbrace{\frac{\partial N_i}{\partial p_j}}_{+}\underbrace{\frac{\partial p_j}{\partial k_i}}_{-}\right)}^{\text{Consumer effect}} + \overbrace{\alpha\left(f_i\underbrace{\frac{\partial Y_i}{\partial k_i}}_{-} + f_j\underbrace{\frac{\partial Y_j}{\partial k_i}}_{-}\right)}^{\text{CP effect}} + \overbrace{\left(\underbrace{\frac{d\alpha}{dk_i}}_{>0}\Pi_c^c\right)}^{\text{CDN effect}} > 0. \tag{1.32}$$

We now observe three separate effects: a positive consumer effect, a negative CP effect and a positive 'CDN effect'. The dynamics in the consumer effect are as before, however, the CP effect now consists only of two direct effects. On the one hand, a capacity increase in network i reduces the congestion problem and hence the benefit from prioritization $\partial Y_i/\partial k_i < 0$. On the other hand, it also attracts consumers from network j to join network i and makes thereby prioritization in network j less attractive $\partial Y_j/\partial k_i < 0$, resulting again in a negative CP effect in total. The CDN effect reflects the fact that as capacity increases the ISP obtains a larger share of the CDN profits. This has mainly two reasons. First, increasing capacity k_i reduces

CDN profits $d\Pi_c/dk_i < 0$ (see CP effect). Secondly, increasing capacity increases the outside option of an ISP, resulting in a higher share of obtainable CDN profits and a positive CDN effect.[17]

In figure 1.1 we now illustrate the magnitude of the different effects for various levels of initial symmetric network capacity k. Proposition 1.6 summarizes the main findings of the illustrated results.

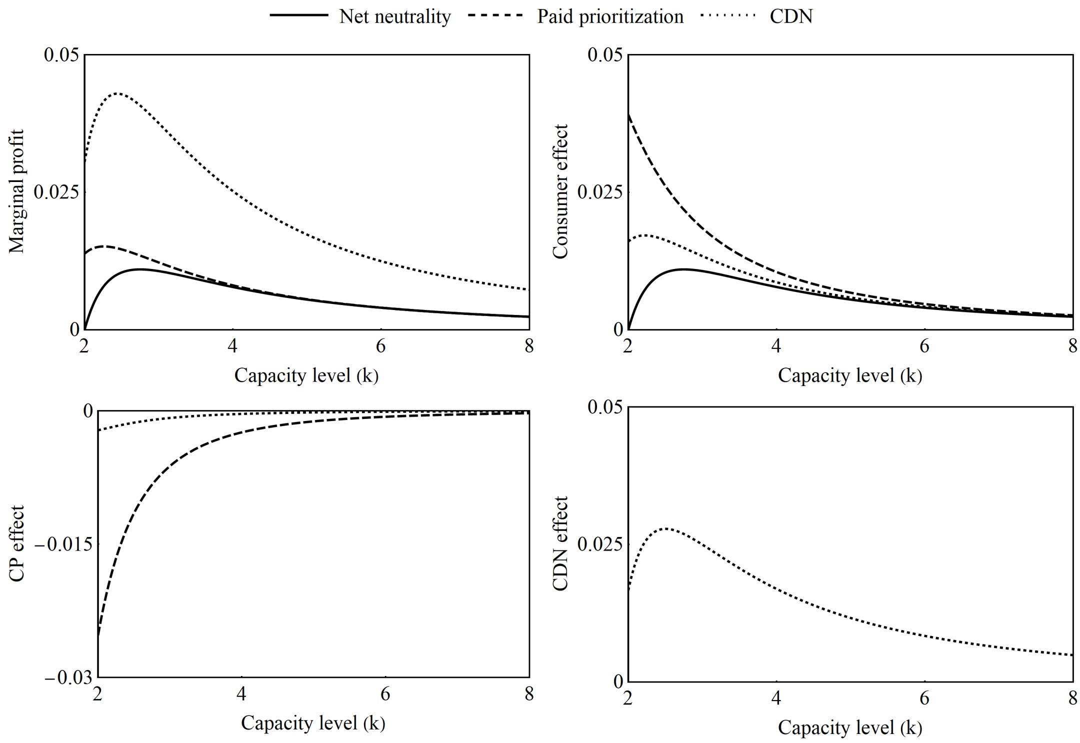

FIGURE 1.1: Comparison of investment incentives

Proposition 1.6 *Incentives to invest in network capacity are highest in the CDN case. Paid prioritization leads to higher investment incentives than a neutral regime if capacity is scarce* $k \leq \overline{k}$.

Proof. See Appendix. □

First, note that the consumer effect is positive in all regimes while the CP effect is negative in the two prioritization regimes. In the CDN case there is an additional positive CDN effect. Those effects, however, differ in magnitude.

Starting with the consumer effect we would first like to mention that the direct effect $\partial N_i/\partial k_i$ is strongest in the neutral regime. Since a tiered quality scheme already reduces the congestion problem, the marginal effect of capacity expansion is higher when the congestion problem is severe, as in the single-queue (neutral) regime. This means, however, that the strategic effect introduced by $\partial p_j/\partial k_i$ must be the driving

[17] We refer to the proof of Proposition 1.6 for details.

force behind the ranking in magnitude displayed in the top right graph of figure 1.1. As explained in section 1.4.2, prioritization leads to a more elastic consumer market. Hence, the market share reaction with respect to rival's prices $\partial N_i/\partial p_j$ is more strongly pronounced in the prioritization regimes. For the same reason, however, the strategic response by ISP j to an increase in capacity k_i is less pronounced in the prioritization regimes. As the consumer market share is more elastic, prices p_j are decreased to a lower extent than in the neutral regime. The strategic effect combined with a more elastic consumer market results in a stronger consumer effect in the prioritization regimes.

The CP effect is negative in both prioritization cases, however, their composition differs. While under paid prioritization only the direct effect on the proprietary network $\partial Y_i/\partial k_i < 0$ is taken into account, in the CDN solution direct effects of both networks are taken into account. The main driver for the difference in magnitude is, however, the weighting factor α in the CDN case, such that in a CDN environment ISPs do not fully internalize the negative effect on the CP market side when deciding on investment in network capacity. In addition to the less pronounced CP effect, ISPs obtain an additional positive CDN effect resulting in highest total marginal profits from capacity investment.

The comparison between the neutral and the paid prioritization regime depends on initial capacity levels.[18] If capacity is scarce $k \leq \overline{k}$ the stronger consumer effect in the discriminatory regime dominates the neutral regime even in light of the negative CP effect. If capacity is abundant $k > \overline{k}$ on the other hand, consumer effects are virtually identical as high overall capacity makes prioritization irrelevant such that the negative CP effect prevails, yielding higher investment incentives in the neutral regime. In light of existing QoS differentiation measures and global efforts to incentivize broadband investment, we consider the case of scarcity to be more relevant.

1.6 Conclusion

We analyzed equilibrium outcomes under different QoS practices and showed that discriminatory regimes are superior in terms of static efficiency as they allocate existing capacity more efficiently, while at the same time competition for consumers is strengthened, resulting in lower consumer prices and higher network quality in both discriminatory regimes compared to a neutral regime. The extent to which consumers benefit, however, depends on the way how prioritization is achieved. While prices are lowest under paid prioritization, consumer prices increase with the use of CDNs, as ISPs lack the additional incentive to attract consumers to make prioritization more valuable.

[18]The critical capacity level is $\overline{k} \approx 6.45$. Details can be found in the proof of Proposition 1.6.

Regarding investment incentives we showed that both discriminatory regimes lead to higher investment in network capacity than the neutral regime as long as capacity is scarce, while investment is highest in a CDN environment irrespective of the initial capacity level. Under paid prioritization marginal profits obtained from the consumer market side are higher than in the neutral regime, while marginal profits obtained from the CP side are negative as capacity expansion makes prioritization less valuable. In a CDN scenario this detrimental effect on the CP side is not fully internalized, while at the same time ISPs are able to capture a larger fraction of CDN profits when network capacity is expanded, resulting in high investment incentives.

We would like to mainly draw two policy conclusions where the first is driven by our efficiency result. As long as content is heterogeneous and network capacity is scarce, a tiered-quality scheme increases efficiency. This result is not driven by the assumption that total demand on the consumer market is inelastic, as a discriminatory regime simultaneously reduces consumer prices. Also, since the best-effort quality remains free of charge no CPs are excluded from the market. For the second conclusion one should note that the general debate on net neutrality tends to focus on ISP practices, while the use of CDNs is barely mentioned. Our results suggest that while the outcome with CDNs is welfare equivalent to the classical paid prioritization, consumer surplus is lower in the presence of CDNs due to higher prices. Focusing on static efficiency and having consumer welfare in mind, a regime of paid prioritization is therefore to be preferred. If the primary policy goal is, however, investment in network infrastructure then our results suggest that a CDN environment is to be preferred over paid prioritization.

We would also like to point out limitations of our analysis and where future research could be headed. First, we implicitly assume that from a technical perspective contracting with a CDN is equivalent to direct prioritization between ISPs and CPs. Here, a more nuanced analysis could refine the comparison with respect to efficiency. Also, we modeled the contractual relationship between ISPs and CDNs in rather general way. Here, industry specific payment structures (access pricing, etc.) could provide further insights. Lastly, one could alter the industry structure in the upstream market and introduce competition between CDNs.

1.A Appendix

1.A.1 Omitted analysis

Market share reactions

For the consumer market share we define an ancillary equation

$$\Delta_N = N_1 - \hat{x} \tag{1.33}$$

where $\hat{x}$ denotes the indifferent consumer on the Hotelling line as in (1.11). To obtain the market share reaction $\partial N_1/\partial p_i$ we then totally differentiate $\Delta_N = 0$ with respect to consumer prices p_i such that

$$\frac{\partial N_1}{\partial p_i} = -\frac{\partial \Delta_N/\partial p_i}{\partial \Delta_N/\partial N_1}. \tag{1.34}$$

while $\partial N_2/\partial p_i = -\partial N_1/\partial p_i$ due to full market coverage. In the case of a prioritization regime we additionally define ancillary equations for the share of prioritized content:

$$\Delta_{Y_i} = Y_i - \left(1 - \hat{\theta}_i\right),\ i = \{1, 2\}. \tag{1.35}$$

Reactions with respect to consumer prices $\partial Y_i/\partial p_j$, $\partial N_i/\partial p_j$ and prioritization fees $\partial Y_i/\partial f_j$, $\partial N_i/\partial f_j$ for $i, j = \{1, 2\}$ are then obtained by totally differentiating equations $\Delta_N = 0$, $\Delta_{Y_1} = 0$ and $\Delta_{Y_2} = 0$. Market share reactions $\partial Y_i/\partial p_j, \partial N_i/\partial p_j$ are then determined by the solution to

$$\frac{d\Delta_Z}{dp_i} = \frac{\partial \Delta_Z}{\partial p_i} + \frac{\partial \Delta_Z}{\partial N_i}\frac{\partial N_i}{\partial p_i} + \frac{\partial \Delta_Z}{\partial Y_i}\frac{\partial Y_i}{\partial p_i} + \frac{\partial \Delta_Z}{\partial Y_j}\frac{\partial Y_j}{\partial p_i} = 0 \tag{1.36}$$

where $\Delta_Z = \{\Delta_N, \Delta_{Y_i}, \Delta_{Y_j}\}$ and $i, j = \{1, 2\}$. Market share reactions with respect to prioritization fees $\partial Y_i/\partial f_j, \partial N_i/\partial f_j$ can be obtained by an equivalent procedure.

Investment incentives

First we outline how we obtain reactions $\partial N_j/\partial k_i, \partial Y_j/\partial k_i, \partial p_j/\partial k_i$ and $\partial f_j/\partial k_i$ for $j = \{1, 2\}$. We will demonstrate the procedure in the paid prioritization case as it can easily be adjusted to yield the reactions in the other regimes. We make extensive use of the implicit function theorem by totally differentiating the first order conditions of ISPs i and j as well as the ancillary equations $\Delta_N = 0$, $\Delta_{Y_i} = 0$ and $\Delta_{Y_j} = 0$ with respect to k_i. The result is the following system of equations where for $Z = \{\Delta_N, \Delta_{Y_i}, \Delta_{Y_j}, \partial\Pi_i/\partial p_i, \partial\Pi_i/\partial f_i, \partial\Pi_j/\partial p_j, \partial\Pi_j/\partial f_j\}$ we have

$$\begin{aligned}\frac{dZ}{dk_i} &= \frac{\partial Z}{\partial k_i} + \frac{\partial Z}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial Z}{\partial p_j}\frac{\partial p_j}{\partial k_i} + \frac{\partial Z}{\partial f_i}\frac{\partial f_i}{\partial k_i} + \frac{\partial Z}{\partial f_j}\frac{\partial f_j}{\partial k_i} \\ &\quad + \frac{\partial Z}{\partial N_1}\frac{dN_1}{dk_i} + \frac{\partial Z}{\partial Y_i}\frac{dY_i}{dk_i} + \frac{\partial Z}{\partial Y_j}\frac{dY_j}{dk_i} = 0,\end{aligned} \tag{1.37}$$

where for $W = \{N_1, Y_i, Y_j\}$ we have

$$\frac{dW}{dk_i} = \frac{\partial W}{\partial k_i} + \frac{\partial W}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial W}{\partial p_j}\frac{\partial p_j}{\partial k_i} + \frac{\partial W}{\partial f_i}\frac{\partial f_i}{\partial k_i} + \frac{\partial W}{\partial f_j}\frac{\partial f_j}{\partial k_i}. \tag{1.38}$$

We now turn to the definition of investment incentives. Starting with the neutral regime, marginal profits $d\Pi_i/dk_i$ with $\Pi_i = p_i N_i$ can be written as

$$\frac{d\Pi_i}{dk_i} = \frac{\partial \Pi_i}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial \Pi_i}{\partial N_i}\left(\frac{\partial N_i}{\partial k_i} + \frac{\partial N_i}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial N_i}{\partial p_j}\frac{\partial p_j}{\partial k_i}\right).$$

Imposing symmetry and evaluating at equilibrium values $p_i = p_j = p^n$ allows us to further make use of the envelope theorem, yielding the final expression.

$$\frac{d\Pi_i}{dk_i} = \underbrace{\left(N_i + p_i\frac{\partial N_i}{\partial p_i}\right)}_{=0}\frac{\partial p_i}{\partial k_i} + p_i\left(\frac{\partial N_i}{\partial k_i} + \frac{\partial N_i}{\partial p_j}\frac{\partial p_j}{\partial k_i}\right). \tag{1.39}$$

Similarly, in the case of paid prioritization with $\Pi_i = p_i N_i + f_i Y_i$ we obtain

$$\begin{aligned}\frac{d\Pi_i}{dk_i} &= \frac{\partial \Pi_i}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial \Pi_i}{\partial N_i}\left(\frac{\partial N_i}{\partial k_i} + \frac{\partial N_i}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial N_i}{\partial p_j}\frac{\partial p_j}{\partial k_i} + \frac{\partial N_i}{\partial f_i}\frac{\partial f_i}{\partial k_i} + \frac{\partial N_i}{\partial f_j}\frac{\partial f_j}{\partial k_i}\right)\\ &+ \frac{\partial \Pi_i}{\partial f_i}\frac{\partial f_i}{\partial k_i} + \frac{\partial \Pi_i}{\partial Y_i}\left(\frac{\partial Y_i}{\partial k_i} + \frac{\partial Y_i}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial Y_i}{\partial p_j}\frac{\partial p_j}{\partial k_i} + \frac{\partial Y_i}{\partial f_i}\frac{\partial f_i}{\partial k_i} + \frac{\partial Y_i}{\partial f_j}\frac{\partial f_j}{\partial k_i}\right).\end{aligned} \tag{1.40}$$

Imposing symmetry $k_i = k_j = k$, evaluating at equilibrium values $p_i = p_j = p^p$, $f_i = f_j = f^p$, and applying the envelope theorem yields

$$\begin{aligned}\frac{d\Pi_i}{dk_i} &= \underbrace{\left(N_i + p_i\frac{\partial N_i}{\partial p_i} + f_i\frac{\partial Y_i}{\partial p_i}\right)}_{=0}\frac{\partial p_i}{\partial k_i} + p_i\left(\frac{\partial N_i}{\partial k_i} + \frac{\partial N_i}{\partial p_j}\frac{\partial p_j}{\partial k_i} + \underbrace{\frac{\partial N_i}{\partial f_j}}_{=0}\frac{\partial f_j}{\partial k_i}\right)\\ &+ \underbrace{\left(Y_i + p_i\frac{\partial N_i}{\partial f_i} + f_i\frac{\partial Y_i}{\partial f_i}\right)}_{=0}\frac{\partial f_i}{\partial k_i} + f_i\left(\frac{\partial Y_i}{\partial k_i} + \frac{\partial Y_i}{\partial p_j}\frac{\partial p_j}{\partial k_i} + \underbrace{\frac{\partial Y_i}{\partial f_j}}_{=0}\frac{\partial f_j}{\partial k_i}\right).\end{aligned} \tag{1.41}$$

Using $\tilde{\Pi}_i := \Pi_i + \alpha\Pi_c$ with $\Pi_i = p_i N_i$, $\Pi_c = f_i Y_i + f_j Y_j$ and $\alpha = F^c/\Pi_c$ in the CDN case we obtain

$$\begin{aligned}\frac{d\tilde{\Pi}_i}{dk_i} &= \frac{d\Pi_i}{dk_i} + \alpha\frac{d\Pi_c}{dk_i} + \frac{d\alpha}{dk_i}\Pi_c\\ &= \frac{\partial \Pi_i}{\partial k_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial \Pi_i}{\partial N_i}\left(\frac{\partial N_i}{\partial k_i} + \frac{\partial N_i}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial N_i}{\partial p_j}\frac{\partial p_j}{\partial k_i} + \frac{\partial N_i}{\partial f_i}\frac{\partial f_i}{\partial k_i} + \frac{\partial N_i}{\partial f_j}\frac{\partial f_j}{\partial k_i}\right)\\ &+ \alpha\left[\frac{\partial \Pi_c}{\partial f_i}\frac{\partial f_i}{\partial k_i} + \frac{\partial \Pi_c}{\partial Y_i}\left(\frac{\partial Y_i}{\partial k_i} + \frac{\partial Y_i}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial Y_i}{\partial p_j}\frac{\partial p_j}{\partial k_i} + \frac{\partial Y_i}{\partial f_i}\frac{\partial f_i}{\partial k_i} + \frac{\partial Y_i}{\partial f_j}\frac{\partial f_j}{\partial k_i}\right)\right.\\ &+ \left.\frac{\partial \Pi_c}{\partial f_j}\frac{\partial f_j}{\partial k_i} + \frac{\partial \Pi_c}{\partial Y_j}\left(\frac{\partial Y_j}{\partial k_i} + \frac{\partial Y_j}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial Y_j}{\partial p_j}\frac{\partial p_j}{\partial k_i} + \frac{\partial Y_j}{\partial f_i}\frac{\partial f_i}{\partial k_i} + \frac{\partial Y_j}{\partial f_j}\frac{\partial f_j}{\partial k_i}\right)\right]\\ &+ \frac{d\alpha}{dk_i}\Pi_c.\end{aligned} \tag{1.42}$$

Evaluating at equilibrium values $p_i = p_j = p^c$, $f_i = f_j = f^c$ for the symmetric case $k_i = k_j = k$ and applying the envelope theorem yields

$$\begin{aligned}\frac{d\tilde{\Pi}_i}{dk_i} &= \underbrace{\left(N_i + p_i\frac{\partial N_i}{\partial p_i}\right)}_{=0}\frac{\partial p_i}{\partial k_i} + p_i\left(\frac{\partial N_i}{\partial k_i} + \frac{\partial N_i}{\partial p_j}\frac{\partial p_j}{\partial k_i} + \underbrace{\frac{\partial N_i}{\partial f_i}}_{=0}\frac{\partial f_i}{\partial k_i} + \underbrace{\frac{\partial N_i}{\partial f_j}}_{=0}\frac{\partial f_j}{\partial k_i}\right)\\ &+ \alpha\left[\underbrace{\left(Y_i + f_i\frac{\partial Y_i}{\partial f_i} + f_j\frac{\partial Y_j}{\partial f_i}\right)}_{=0}\frac{\partial f_i}{\partial k_i} + f_i\left(\frac{\partial Y_i}{\partial k_i} + \frac{\partial Y_i}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial Y_i}{\partial p_j}\frac{\partial p_j}{\partial k_i}\right)\right.\\ &\left.+ \underbrace{\left(Y_j + f_i\frac{\partial Y_i}{\partial f_j} + f_j\frac{\partial Y_j}{\partial f_j}\right)}_{=0}\frac{\partial f_j}{\partial k_i} + f_j\left(\frac{\partial Y_j}{\partial k_i} + \frac{\partial Y_j}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial Y_j}{\partial p_j}\frac{\partial p_j}{\partial k_i}\right)\right]\\ &+ \frac{d\alpha}{dk_i}\Pi_c.\end{aligned} \tag{1.43}$$

Investment incentives in the CDN case can then be written as:

$$\begin{aligned}\frac{d\tilde{\Pi}_i}{dk_i} &= p_i\left(\frac{\partial N_i}{\partial k_i} + \frac{\partial N_i}{\partial p_j}\frac{\partial p_j}{\partial k_i}\right)\\ &+ \alpha\left[f_i\left(\frac{\partial Y_i}{\partial k_i} + \frac{\partial Y_i}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial Y_i}{\partial p_j}\frac{\partial p_j}{\partial k_i}\right) + f_j\left(\frac{\partial Y_j}{\partial k_i} + \frac{\partial Y_j}{\partial p_i}\frac{\partial p_i}{\partial k_i} + \frac{\partial Y_j}{\partial p_j}\frac{\partial p_j}{\partial k_i}\right)\right]\\ &+ \frac{d\alpha}{dk_i}\Pi_c.\end{aligned} \tag{1.44}$$

Finally, using $\partial Y_i/\partial p_i = -\partial Y_j/\partial p_i$ for $i \neq j$ we obtain the final simplified form. Furthermore, using $\alpha = F^c/\Pi_c = (\Pi_i^A - \Pi_i^c)/\Pi_c^c$ we obtain

$$\frac{d\alpha}{dk_i} = \frac{\partial\alpha}{\partial\Pi_i^A}\frac{d\Pi_i^A}{dk_i} + \frac{\partial\alpha}{\partial\Pi_i^c}\frac{d\Pi_i^c}{dk_i} + \frac{\partial\alpha}{\partial\Pi_c^c}\frac{d\Pi_c^c}{dk_i} \tag{1.45}$$

where $d\Pi_i^c/dk_i$ and $d\Pi_c^c/dk_i$ are derived above, while $d\Pi_i^A/dk_i$ is obtained precisely as in (1.37) and (1.38) applied to the asymmetric game structure outlined in the proof of Lemma 1.2.

1.A.2 Omitted proofs

Proof of Lemma 1.1

Proof. To prove the result define $\overline{f}_i$ such that

$$\hat{\theta}_i = \frac{\overline{f}_i N_i}{N_i(q_i^p - q_i^n)} = 1.$$

Then, solving $\partial\Pi_i/\partial p_i = 0$ for p_i and substituting we get (independently of $\widehat{\theta}_j \in (0,1)$ or $\widehat{\theta}_j = 1$)

$$\left.\frac{\partial\Pi_i}{\partial f_i}\right|_{f_i=\overline{f}_i} = -\frac{3k}{2(k-\widehat{x})} < 0$$

where $\widehat{x}$ denotes the indifferent consumer obtained as in (1.11). Hence, decreasing $\overline{f}_i$ and thus offering prioritization would lead to higher profits Π_i. □

Proof of Lemma 1.2

Proof. We consider three different sub-game outcomes: a symmetric outcome where both ISPs contract with the CDN, an asymmetric outcome where only one ISP contracts with the CDN and the case where no ISP contracts with the CDN. The last case leads to zero profits for the CDN such that it suffices to show that profits in the other two cases are weakly positive to exclude this case.

To ease notation let $\Pi_c^c = 2f^cY^c$ and $\Pi_i^c = p^c/2$ denote the equilibrium profits of the sub-game outlined in section 1.4.3, and $\Pi_i^p = p^p/2 + f^pY^p$ be the equilibrium ISP profit from section 1.4.2. Further consider the following asymmetric game where ISP j delegates prioritization to the CDN, while ISP i does not contract with the CDN. As the lump-sum transfers do not affect the price choice in the subsequent simultaneous move game, we can solve for the asymmetric solution $(p_i^A, p_j^A, f_i^A, f_j^A)$ by following the same steps as outlined in section 1.4.3 such that

$$(p_i^A, f_i^A) = \arg\max_{p_i, f_i} \Pi_i^A = p_iN_i + f_iY_i|_{p_j=p_j^A, f_j=f_j^A}, \tag{1.46}$$

$$p_j^A = \arg\max_{p_j} \Pi_j^A = p_jN_j|_{p_i=p_i^A, f_i=f_i^A, f_j=f_j^A}, \tag{1.47}$$

$$f_j^A = \arg\max_{f_j} \Pi_c^A = f_jY_j|_{p_i=p_i^A, p_j=p_j^A, f_i=f_i^A}. \tag{1.48}$$

Equilibrium values are then given by

$$f_i^A = \frac{kN_i^A\left(-k + N_i^A + \sqrt{k(k-N_i^A)}\right)}{(k(k-N_i^A))^{3/2}}, \tag{1.49}$$

$$f_j^A = \frac{(N_i^A-1)^2}{(k+N_i^A-1)\left(k+\sqrt{k(k+N_i^A-1)}\right)}, \tag{1.50}$$

$$p_j^A = \frac{1-N_i^A}{N_i^A}\left(p_i^A + f_i^A\frac{k}{(k-N_i^A)N_i^A}\right), \tag{1.51}$$

$$\begin{aligned} p_i^A = &\frac{1}{N_i^A}\left(1 - \frac{k}{\sqrt{k(k-N_i^A)}}\right) + \frac{-2k+2N_i^A+3\sqrt{k(k-N_i^A)}}{2(k-N_i^A)^2} \\ &+ \frac{1}{2}N_i^A\left(\frac{(-2k-3N_i^A+3)k^2}{(N_i^A-1)^2(k(k+N_i^A-1))^{3/2}} - \frac{2}{(k-N_i^A)^2} + \frac{2}{(N_i^A-1)^2} + 4\right). \end{aligned} \tag{1.52}$$

resulting in

$$Y_i^A = \frac{k-\sqrt{k(k-N_i^A)}}{N_i^A} \quad \text{and} \quad Y_j^A = 1 - \frac{k+N_i^A-1}{\sqrt{k(k+N_i^A-1)}+k+N_i^A-1} \tag{1.53}$$

while N_i^A is implicitly defined by $\Delta_{N^A} = 0$ with

$$\begin{aligned}\Delta_{N^A} = &\frac{k - 2\sqrt{k(k - N_i^A)}}{(k - N_i^A)^2} \\ &+ \frac{1}{1 - N_i^A}\left[4 + \frac{N_i^A(k + 2N_i^A - 2)k^2}{(1 - N_i^A)(k(k + N_i^A - 1))^{3/2}} - 3N_i^A + \frac{\sqrt{k(k + N_i^A - 1)}}{2(k + N_i^A - 1)^2} - \frac{1}{1 - N_i^A}\right] \\ &+ \frac{1}{(N_i^A)^2}\left[1 - 6(N_i^A)^3 + \frac{1}{2}\left(\frac{k^2(2k - 2N_i^A + 1)}{(k(k - N_i^A))^{3/2}} - 2\right) N_i^A - \frac{k}{\sqrt{k(k - N_i^A)}}\right]. \end{aligned} \tag{1.54}$$

We denote the payoffs evaluated at the asymmetric equilibrium solution simply as Π_i^A, Π_j^A and Π_c^A.

Starting with the symmetric outcome outlined in section 1.4.3, an ISP will not deviate from the acceptance of an offer F^c if $\Pi_i^c + F^c \geq \Pi_i^A$ such that the optimal offer from the point of view of an CDN is given by $F^c = \Pi_i^A - \Pi_i^c$. Also, the CDN's participation constraint must be satisfied such that $\Pi^c - 2F^c \geq 0$. Substituting F^c and rearranging we obtain the sufficient condition

$$\Pi_c^c + 2\Pi_i^c - 2\Pi_i^A \geq 0 \tag{1.55}$$

for the existence of an offer F^c which is accepted by both ISPs.

Turning to the asymmetric case we need acceptance of an offer $\hat{F}$ such that $\Pi_j^A + \hat{F} \geq \Pi_i^p$ where $\hat{F} = \Pi_i^p - \Pi_j^A$ is the lowest offer accepted by one ISP, while the offer to the other ISP can simply be set to $-\infty$ to make sure that only one ISP contracts with the CDN. Similarly, we need to make sure that the participation constraint of the CDN is satisfied such that $\Pi_c^A - \hat{F} \geq 0$ or after substituting

$$\Pi_c^A + \Pi_j^A - \Pi_i^p \geq 0. \tag{1.56}$$

In order for the symmetric case to be sub-game perfect we additionally require that the achievable payoff from contracting with both ISPs is higher than in the asymmetric case such that $\Pi^c - 2F^c \geq \Pi_c^A - \hat{F}$ or after substituting and rearranging

$$\Pi_c^c + 2\Pi_i^c + \Pi_i^p - \Pi_c^A - 2\Pi_i^A - \Pi_j^A \geq 0. \tag{1.57}$$

Conditions (1.55) - (1.57) are sufficient to prove existence of symmetric fees F^c which are accepted by both ISPs and satisfy the participation constraint of the CDN, and furthermore these conditions assure that the symmetric outcome is preferred to the asymmetric case, assuring that the equilibrium of the sub-game characterized in section 1.4.3 is indeed sub-game perfect. As all three conditions depend on the asymmetric solution, we address the implicit definition of N_i^A in (1.54) by evaluating equilibrium payoffs Π_c^A, Π^A and Π_j^A for a given level k at the root to $\Delta_{N^A} = 0$. We can then perform numerical analysis for arbitrary values of k to verify that all three conditions are satisfied. An illustration of the numerical analysis can be seen in the following figure where 'sym' refers to the LHS of (1.55), 'asym' to the LHS of (1.56) and 'comp' to the LHS of (1.57).

Following the same procedure one can verify that for given offers $F_i = F_j = F^c$ there also exists the reject/reject equilibrium in the offer stage which leads to payoffs Π_i^p for both ISPs.

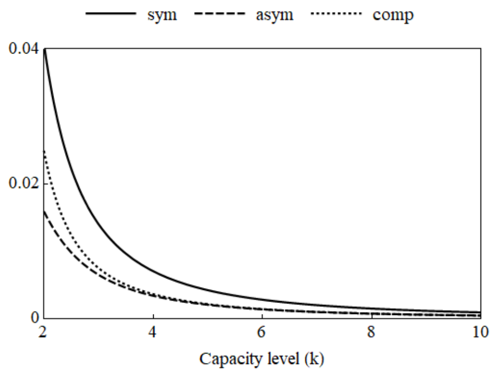

FIGURE 1.2: Illustration of conditions (1.55)-(1.57)

This equilibrium is payoff dominated by the accept/accept equilibrium and therefore is subject to our refinement. □

Proof of Proposition 1.1

Proof. As the consumer market is inelastic, the equivalence follows directly from $\hat{\theta}^c = \hat{\theta}^p$. □

Proof of Lemma 1.3

Proof. This result follows from the definition of $V(\hat{\theta})$ in (1.25). After basic simplifications we obtain $V(\hat{\theta}) = 3/2 - \hat{\theta}/(2k-1) - 2k/(2k-(1-\hat{\theta}))$ and $V(1) = (2k-3)/(4k-2)$. Comparing $V(\hat{\theta}) > V(1)$ then reduces to $(1-\hat{\theta}) > 0$, which is satisfied for $\hat{\theta} \in (0,1)$. □

Proof of Proposition 1.2

Proof. The result in i.) follows from Lemma 1.3. For ii.) we rearrange $p^n > p^c$ to $\psi > (8k^2 - 8k + 1)/(4k-3)$. Squaring both sides and basic simplification steps lead to $(4k-3)^2(4k^2 - 2k - 1) > 0$ which is true by Assumption 1.1. For $p^c > p^p$ we immediately see that $p^c - p^p = f^p 4k/(2k-1) > 0$. Point iii.) follows directly from i.) and ii.). □

Proof of Proposition 1.3

Proof. The inequality $S_{CP}(f^p, \hat{\theta}^p) = S_{CP}(f^c, \hat{\theta}^c) < S_{CP}(f^n, \hat{\theta}^n)$ reduces to $2\hat{\theta}^c = 2\hat{\theta}^p < 1$. As $\partial\hat{\theta}^p/\partial k = \partial\hat{\theta}^c/\partial k > 0$ it follows from $\lim_{k\to\infty} \hat{\theta}^p = 1/2$ that $2\hat{\theta}^p = 2\hat{\theta}^c < 1$. □

Proof of Proposition 1.4

Proof. First note that $S_{ISP}(p^c, f^c, \hat{\theta}^c) > S_{ISP}(p^p, f^p, \hat{\theta}^p)$ follows from the proof of Proposition 1.2 as it boils down to the difference in consumer prices. The second inequality $S_{ISP}(p^n, f^n, \hat{\theta}^n) > S_{ISP}(p^c, f^c, \hat{\theta}^c)$ can be rearranged to $2k(1+12k^2+5\psi+\psi^2) < \psi^2+4k^2(5+4\psi)$. Substituting $\psi^2 = 2k(2k-1)$ and rearranging yields $(16k^2 - 14k + 2)/(8k-5) < \psi$. Squaring both sides and rearranging yields $(5-8k)^2(3k-2) > 0$, which is true. □

Proof of Proposition 1.5

Proof. Follows from Lemma 1.3 and Proposition 1.2. □

Proof of Proposition 1.6

Proof. Following the procedure outlined in Appendix 1.A.1 we obtain closed form solutions for investment incentives in all three QoS regimes. In the case of net neutrality and paid prioritization the investment incentives only depend on the initial symmetric capacity level k. As investment incentives in the CDN case partly depend on the asymmetric solution outlined in the proof of Lemma 1.2), we obtain a final form depending on k and an asymmetric market share N_i^A which is implicitly defined by $\Delta_{N^A} = 0$ in (1.54). We denote investment incentives in the three regimes therefore as $\kappa^n(k)$, $\kappa^p(k)$ and $\kappa^c(k, N_i^A)$ but refrain from stating explicit expressions at this point.

Comparing $\kappa^n(k)$ and $\kappa^p(k)$ reveals a critical level $\overline{k} \approx 6.45$ such that $\kappa^n(k) \leq \kappa^p(k)$ for $k \leq \overline{k}$ and $\kappa^n(k) > \kappa^p(k)$ for $k > \overline{k}$. For the comparison to the CDN case we rely on a numerical approach where we evaluate $\kappa^c(k, N_i^A))$ for a given level k at the root N_i^A to $\Delta_{N^A} = 0$. The performed analysis reveals $\kappa^c(k, N_i^A) > \kappa^n(k)$ and $\kappa^c(k, N_i^A) > \kappa^p(k)$ while $\lim_{k\to\infty} \big(\kappa^c(k, N_i^A) - \kappa^n(k)\big) = \lim_{k\to\infty} \big(\kappa^c(k, N_i^A) - \kappa^p(k)\big) = 0$. $\square$

Chapter 2

Privacy and Platform Competition

Based on Dimakopoulos and Sudaric (2018).

2.1 Introduction

Online platforms often do not charge monetary prices from users but monetize through an advertisement-based business model building on the collection and processing of user data. Typical examples include social networks (e.g. Facebook, LinkedIn), search engines (e.g. Bing, Google) or video platforms (e.g. Youtube, Vimeo). The role of user data in this context is ambiguous. From the platform perspective user data is an input factor which can be used to gain insights about users and improve the targeting of advertisement, resulting in a superior product for potential advertisers. This commodity attribute of data is mirrored to a lesser extent on the user side. Users typically accept some conditions to what extent personal data is collected and processed when using a platform service. In some cases the provision of personal data is necessary to make meaningful use of a platform service (e.g. social networks), while in other cases services do not require the collection of user data per se (e.g. search engines, mail providers, video platforms). In both cases the provision of data from a user perspective can be interpreted as a price the user is willing to accept in exchange for the use of the platform including the display of ads.[19] To put it in terms of platform economics, user data requirements exhibit price characteristics on the one hand, and affect indirect network effects (e.g. targeting) at the same time.

This ambiguity makes it especially hard for policy makers, as standard economic arguments might not be applicable. Indeed, the *European Data Protection Supervisor*

[19] A study by the Pew Research Center (2014) shows that 91 percent of respondents agree that they lost control over how companies collect personal data while 55 percent state that they are willing to share some information in exchange for using a free service. The European Commission (2015), however, reports that 72 percent of internet users worry that they provide too much data online. This indicates that users are aware and willing to exchange personal data for services, however, the actual extent worries them.

(EDPS) argues that competition authorities should take privacy and data related aspects more into account (EDPS, 2014).[20] And indeed, recent cases demonstrate that competition authorities acknowledge the peculiarities of data-driven industries. Germany's *Federal Cartel Office (Bundeskartellamt, BKartA)* initiated investigations against Facebook in 2016 based on alleged abuse of market power. In particular, the BKartA investigates whether Facebook uses its dominant position in the market for social networks to expand the terms of service outlining how much data is collected and processed by the platform.[21] Therefore, we want to shed some light on the role of competition intensity in a two-sided market framework when users provide data and this data is monetized on the opposing market side.[22]

We analyze a setting of two competing ad-financed platforms in a two-sided market framework. On the user market side, platforms strategically set the required level of data provision, to which users have to agree to obtain access to the platform service. Platforms process this user data to sell improved ad targeting on the advertiser market side. While users incur disutility from providing data (privacy concerns, opportunity costs), they benefit from seeing more relevant ads. Users and advertisers are assumed to single-home.

Our model predicts that platforms will extract a distorted amount of data compared to the efficient benchmark. The distortion is induced through the one-sided monetization in a way that platforms do not perfectly balance the costs of data provision, i.e. privacy costs incurred by users, against the targeting benefits on both market sides, but put too much or too little weight on the benefit captured by the monetized market side. This distortion depends on the net effect of cross-group externalities as well as the degree of competition intensity on both market sides. If targeting benefits are small or competition is weak, an inefficiently high level of data is collected. On the other hand, if competition is strong or targeting benefits sufficiently outweigh nuisance costs, too little data is collected. From the point of view of consumers the competitive level of data provision is always too high, suggesting that applying a consumer standard to online platforms leads to underprovision of personal data. The competitive equilibrium level of data provision, however, is monotone in the degree of competition intensity: the weaker the competition on either side of the market, the higher the equilibrium amount of data provision. This result is interesting because it

[20] Whether competition authorities should incorporate aspects of privacy and data protection is, however, controversial. For arguments in favor we refer to Stucke and Grunes (2016), arguments against can be found e.g. in Cooper (2013).

[21] Bundeskartellamt, 'Bundeskartellamt initiates proceeding against Facebook on suspicion of having abused its market power by infringing data protection rules', Press Release, 2 March 2016, `http://www.bundeskartellamt.de/SharedDocs/Meldung/EN/Pressemitteilungen/2016/02_03_2016_Facebook.html`.

[22] Classical examples include ad-based business models where data is used to improve ad targeting or matching / recommendation platforms, where users are presented offers which become more relevant the more the platform knows about its users. For illustration purposes we stick to the example of targeted advertising and refer to the extension part of this paper for a more general consideration of cross-group externalities, i.e. also the possibility of users enjoying the presence of firm's offers.

does not follow the common two-sided platform logic that less elasticity on one side typically decreases the other side's price.

Our findings indicate that the inefficiency of data provision can be reduced by careful privacy regulation or competition policies on either market side. One interpretation of this result is that (competition) policy measures in these data-driven industries should take into account the effects they have on the extent of private data collection.

We also consider a variety of extensions to this setup. In the first one we depart from the assumption that platforms are restricted in their price setting on the user side, and allow for non-zero user prices. In fact, lifting the restriction leads to an efficient level of collected data, while user prices can be positive, negative (or zero). This gives rise to two interpretations. The first is a Coasian one, where establishing the missing market on the user side leads to an efficient outcome. This reflects the idea of Laudon (1996) that users should be adequately compensated for the provision of their data, while the problem of the 'data economy' lies precisely in the absence of such a market. The second interpretation is of counterfactual nature. In particular we argue that whenever the unrestricted model would yield positive (negative) user prices, the restricted model exhibits overprovision (underprovision) of user data as platforms can no longer adequately charge or compensate users for collecting data. The second extension considers different degrees of platform collusion and we conclude that the amount of collected data is excessively high under full collusion, while this is not necessarily the case under partial collusion. In the third extension we discuss the robustness of our results with respect to multi-homing and elastic total demand. Lastly, we demonstrate that our results naturally extend to settings with positive cross-group externalities (matching platforms).

2.2 Related literature

Methodologically, our research is related to the literature on platform competition in general and on applications in media markets in particular. We consider a competitive setting with two-sided single-homing which has been analyzed by Armstrong (2006) in a more general framework and later extended in Armstrong and Wright (2007). However, both papers consider the case where platforms engage in two-sided pricing while non-monetary aspects (as e.g. user data) are not modelled. We also share a common component with the literature on media platforms in the sense that we, at least in our baseline model, consider the case of opposing indirect network effects, where advertisers like to reach many users but users dislike the presence of advertisers. This reflects the idea of 'peace and quiet' privacy in Posner (1981) and is a common assumption in the media literature (see Anderson and Gabszewicz (2006) for a review). This setup is used e.g. to study competition in TV markets (see e.g. Anderson and Coate (2005) or Peitz and Valletti (2008)) where platforms do not engage in targeted advertising and therefore the expected revenue per user as well as perceived nuisance are constant. Our research differs in the sense that we endogenize those indirect network effects as we let them to be affected by the level of data collected. The concept of endogenous network effects is captured in Reisinger (2012) where users spend time using platform services and platforms translate this activity into better targeting and reduced nuisance. A similar setup is presented in Bourreau et al. (2018), however the research question differs substantially. The key difference is that in our model the level of data provision is a strategic decision of the competing platforms, while in the two previously mentioned papers consumers voluntarily spend time/provide data on the platforms which changes the competitive dynamics significantly.

We also contribute to the broader literature on efficient provision of personal data and the role of privacy as a competition instrument. The aspect of data provision being a strategic choice made by platforms is captured to some extent by Spiegel (2013) who compares commercial software (full privacy) to adware (positive privacy costs) and shows that adware is welfare superior. De Corniere and De Nijs (2016) consider a setting where a monopolistic platform auctions off advertising slots and decides whether to disclose consumer information (no privacy) or not (privacy). They show that platforms might prefer information disclosure, which comes at the cost of some consumers leaving the market such that from a welfare point of view it is not clear which regime is preferable. Bloch and Demange (2018) present a setting where consumers are heterogeneous with respect to their privacy cost and a monopolistic platform decides how much data to extract. They show that depending on parameter values the amount of data collection can be excessively high. A similar setting is presented in Lefouili and Toh (2017) where a monopolistic platform monetizes on disclosing personal information to third parties. The authors conclude that one of the inefficiencies arising is excessive information disclosure. The mentioned papers consider the case of monopolistic platforms, while we consider the case of competing platforms, allowing for varying degrees of competition intensity on both market sides.

The role of privacy in a competitive environment is considered in Casadesus-Masanell and Hervas-Drane (2015) where firms not only compete in a price dimension but also in a quality dimension which the authors motivate as privacy. They show that compared to a monopolistic firm, competition leads to a higher degree of privacy while increasing competition intensity does not necessarily imply that privacy improves even further. A key assumption in their model is that prices for disclosing consumer information are exogenous, while in our model platforms have market power vis-à-vis advertisers and hence face a tradeoff. They also show that low privacy firms tend to subsidize consumers, while high privacy firms charge positive consumer prices. Similarly, Kummer and Schulte (2016) show empirically that there is a trade-off between money and privacy for users. They analyze mobile application data and find that apps are cheaper when more personal data can be collected. These results reoccur in our two-sided pricing extension as we show that user prices can be positive or negative as well, while the degree of privacy provision is excessively high or low once firms can no longer compensate users for their data provision. To our knowledge there are very few empirical studies examining the interaction between market power and privacy. In fact, the only study we are aware of is Bonneau and Preibusch (2010) who relate the extent of data collection policies of various online services to the competitiveness of the market they are operating in. They show that the more market power a firm has, the more personal information is asked to be provided which is in line with our model.

2.3 Model

We analyze a setting where two symmetric platforms, $i, j \in \{1, 2\}$ with $j \neq i$, compete for advertisers and users. Advertisers and users are distributed uniformly on different Hotelling lines of unit length and are assumed to both single-home. This assumption allows us to focus on the role of competition intensity more clearly.[23] Platforms are located at the ends of the respective Hotelling lines such that platform i is located at location $l_i = 0$ and platform j at $l_j = 1$. Note that on the advertiser and the user side we have distinct Hotelling lines and therefore distinct parameters of transportation costs, which we will later interpret as different degrees of competition intensity. The idea is that the degree of competition faced by platforms does not have to be same for all market sides. For example, online platforms from different segments, such as search engines, social networks, video streaming platforms or mail providers, may all compete for the same advertisers, however competition for users may occur separately and independently of the other segments.

2.3.1 Users

A user located at x on the Hotelling line obtains utility $u_i(x)$ from joining platform i where

$$u_i(x) = \underline{u} - \kappa(d_i) - \nu(d_i)A_i - t_u|l_i - x|. \tag{2.1}$$

The first term of the utility function is a fixed utility component $\underline{u}$ from using platform services, which is the same for both platforms. Second, $\kappa(d_i) \geq 0$ denotes the privacy (opportunity) costs of providing user data d_i to the platform, whereby we assume that costs are strictly convex and twice differentiable, and specifically that $\kappa'(0) = 0$, while $\kappa'(d) > 0$ for all $d > 0$ and $\kappa''(d) > 0$ for all d. Third, users incur nuisance cost $\nu(d) \geq 0$ per advertisements A_i on the platform. We assume that users (weakly) prefer personalized to non-personalized ads, i.e. $\nu(d)$ is a convex and twice differentiable function s.t. $\nu'(d) \leq 0$ and $\nu''(d) \geq 0$. This setup reflects the idea that the more

[23]In Section 2.7 we discuss multi-homing.

relevant an ad, the higher the chance of value creation through a possible follow-up purchase.[24] Finally, users face transportation costs due to horizontal platform differentiation, whereby we assume uniform user distribution on the Hotelling line, i.e. $x \overset{u}{\sim} [0,1]$, while $t_u > 0$ is the associated transportation cost parameter.

Consumers in our baseline model are not charged a monetary price explicitly, which makes our model comparable to e.g. Reisinger (2012). We follow the same line of reasoning as e.g. in Peitz and Reisinger (2016) and Waehrer (2015) that there are some exogenous constraints preventing platforms from charging non-zero consumer prices. This restriction is, however, relaxed in section 2.7.1. In order to join a platform users have to provide some personal data d_i in our model. This is different to the setup in Reisinger (2012) or Bourreau et al. (2018) as in our model platforms can set the level of data which has to be provided by the users, whereas in their models consumers voluntarily provide a certain amount of time. The idea behind our setup is that consumers accept terms and conditions when using a platform which requires them to accept a certain level of data provision or alternatively cases where users have to register for an account by providing personal information before they can use the platform service. This specification on the consumer side allows us to focus on user data d_i as primary strategic aspect for competition.

2.3.2 Advertisers

An advertiser located at a on the Hotelling line obtains an expected profit of $\pi_i(a)$ from posting a single ad on platform i,

$$\pi_i(a) = \tau(d_i)(1 - p_i)X_i - t_a|l_i - a|. \tag{2.2}$$

The interaction with X_i users on platform i generates a normalized expected revenue of 1, if users decide to 'click on the ad', which happens with probability $\tau(d_i)$. The strictly concave and twice differentiable function $\tau(d) \geq 0$ can be interpreted as the targeting ability of platforms: the more data d can be collected from users, the more effective the targeting and hence the higher the probability that a user clicks on this ad, i.e. we have that $\tau'(d) > 0$ and $\tau''(d) < 0$. At the same time we assume that advertisers only pay the platform a price p_i if the ad has been clicked (cost-per-click) such that the expected revenue per user is given by $\tau(d_i)(1 - p_i)$, which is consistent with real-world pricing practices. The second term reflects advertisers transportation costs when joining platform i. Again we assume uniform advertiser distribution on the Hotelling line, i.e. $a \overset{u}{\sim} [0,1]$, and $t_a > 0$ as the transportation cost parameter on the advertiser side.

[24] Note that our set-up allows for positive utility of seeing advertisement as well, as long as this positive utility is again concave in the amount of provided data. However, for sake of clarity we stay with the notion of negative utility of nuisance in the subsequent text and consider the case of positive cross-group externalities as an extension in section 2.7.

2.3.3 Platforms

The business model of platforms in our model is purely ad-based. While they offer (exogenous) platform services ($\underline{u}$) to users, revenue is only generated through presenting ads to users.[25] Platform profits are then given by

$$\Pi_i\left(d_i, p_i\right) = A_i X_i \tau(d_i) p_i, \tag{2.3}$$

i.e. A_i advertisers at platform i pay p_i whenever the platform's users X_i click on an ad with probability $\tau(d_i)$.[26] The crucial novelty in our model is that we assume that besides charging prices to advertisers, platforms extract data d_i from their users. While d_i shares some price characteristics from the point of view of users, data is an essential input factor for the click-probability the advertisers are facing. At the same time we assume that not only the click probability increases through better targeting possibilities but also the nuisance decreases.

2.3.4 Assumptions

We make the following assumptions to ensure full advertiser and user market coverage, allowing us to study environments of full platform competition.[27]

Assumption 2.1 *Competition for advertisers is sufficiently strong, i.e.* $t_a \leq \bar{t}_a$. *This implies that competition for users is sufficiently weak and that there are gains of trade for all advertisers, even without data collection, i.e.*

$$(a) \quad t_u > \nu(0),$$
$$(b) \quad t_a < \tau(0).$$

The upper bound on t_a is given by $\bar{t}_a := \frac{t_u \tau(0) - \nu(0)\tau(0)}{3t_u + \nu(0)}$. This assumption on the upper bound of t_a allows us to isolate effects in a competitive environment. Intuitively, this constitutes a sufficient condition, such that for any level of (symmetric) data provision $d \geq 0$, it is assured that all advertisers obtain non-negative profits. Consequently, competition for advertisers is sufficiently strong.

The condition on the consumer nuisance function, i.e. the necessary condition (a) of Assumption 2.1, can be motivated as follows: no platform will obtain the entire user market, even if all ads were placed on the rival platform. Technically, this is

[25] In Section 2.7 we discuss two-sided pricing.

[26] Note that platforms and advertisers share the profit created by each targeted user on the platform. However, this does not mean that their incentives are perfectly aligned, since platforms additionally care about the number of advertisers joining.

[27] In Section 2.7 we discuss relaxing the full-market coverage assumptions.

established by $t_u > \nu(0)$.[28] The condition on the targeting technology, i.e. the necessary condition (b) of Assumption 2.1, states that even without collecting any data advertisers can still profitably join a platform. In particular we assume that there are gains of trade for all advertisers. Intuitively, this assumption states that there is a positive probability for users to click an ad even if the ad is not targeted at all. And this probability, $\tau(0)$, exceeds the transportation cost incurred by any advertiser t_a, such that no advertisers are excluded, even if too little data is collected.

Assumption 2.2 *The fixed utility component $\underline{u}$ is large enough to ensure full market coverage on the user side.*

Intuitively, the platform service provides sufficient utility such that users are not deterred through the provision of personal data and seeing ads.

The timing of the game is as follows. In the first stage platforms simultaneously set prices p_i and the required level of data d_i to join their platform. In the second stage advertisers and users observe the platforms' choices and simultaneously decide which platform to join, hence determining A_i and X_i.[29] The equilibrium concept is subgame perfection and we solve the game by backward induction.

2.4 Equilibrium analysis

In this section we will first present the results for the second-stage subgame of user and advertiser allocation. Then we will show the efficient and the user-optimal outcome as well as the market outcome in the Subgame Perfect Nash Equilibrium.

2.4.1 Second stage market shares

In the second stage the market shares on the consumer and advertiser side are given by the standard Hotelling procedure. Utilizing the unit length of the Hotelling line, and given full user market coverage due to Assumption 2.2, the number of users joining a platform is then determined by the indifferent consumer $\hat{x} : u_i(\hat{x}) = u_j(\hat{x})$ such that

$$X_i = \hat{x} = \frac{1}{2} + \frac{1}{2t_u}\left[\kappa(d_j) - \kappa(d_i) + \nu(d_j)A_j - \nu(d_i)A_i\right], \qquad X_j = 1 - \hat{x}. \tag{2.4}$$

Similarly, market shares on the advertiser side are given by the indifferent advertiser $\hat{a} : \pi_i(\hat{a}) = \pi_j(\hat{a})$. Note that Assumption 2.1 assures market coverage gross of advertising prices. For now we therefore assume that prices permit full market

[28]Note that $t_u > \nu(0) \Rightarrow t_u > \nu(d)\,\forall d$ because $\nu'(d) \leq 0$. Given any (symmetric) amount of data $d \geq 0$ collected by both platforms, even if all advertisers used platform j such that $A_i = 0$ and $A_i = 1$, at least the user most loyal to platform j, i.e. located directly at l_j, would rather stay at this platform j, even though it is full of ads. In other words, competition for users is sufficiently weak.

[29]We could also consider an alternative timing where advertisers choose first and users last. The outcome is equivalent in our model.

coverage and check later that in equilibrium this is indeed the case. Market shares are then given by

$$A_i = \hat{a} = \frac{1}{2} + \frac{1}{2t_a}\left[\tau(d_i)(1-p_i)X_i - \tau(d_j)(1-p_j)X_j\right], \qquad A_j = 1 - \hat{a}. \tag{2.5}$$

Solving the system of equations given in (2.4) and (2.5) yields unique market shares X_i, X_j, A_i and A_j as functions of data requirements d_i, d_j and prices p_i, p_j. Explicit solutions are provided in the Appendix.

2.4.2 Efficiency benchmark

For the derivation of the welfare-efficient benchmark, we define welfare as the sum of all indirect utilities and profits, anticipating second stage market shares as in 2.4.1, i.e.

$$W\left(d_i, d_j, p_i, p_j\right) = \int_0^{X_i} u_i(x)\mathrm{d}x + \int_{X_i}^1 u_j(x)\mathrm{d}x + \int_0^{A_i} \pi_i(a)\mathrm{d}a + \int_{A_i}^1 \pi_j(a)\mathrm{d}a + \Pi_i + \Pi_j. \tag{2.6}$$

Proposition 2.1 *Welfare is maximized by the unique symmetric solution $(d^o, p^o) = (d_i^o, p_i^o)$ for $i \in \{1, 2\}$, where d^o is characterized by*

$$\kappa'(d^o) = \frac{\tau'(d^o)}{2} - \frac{\nu'(d^o)}{2} \tag{2.7}$$

resulting in equal advertiser and user market shares, i.e. $A_i^o = 1/2$ and $X_i^o = 1/2$. The price p^o can be freely chosen to split the rent between advertisers and platforms.[30]

The welfare-optimal level of data d^o is chosen in a way such that users' marginal cost of data provision $\kappa'(d^o)$ equals the sum of marginal benefits across both market sides, i.e. the marginal benefit of enhanced targeting $\tau'(d^o)/2$ and the marginal benefit of reduced nuisance $-\nu'(d^o)/2$, while the factor 1/2 is due to the symmetric market shares.[31] Furthermore, the optimal level of data provision is independent of transportation cost parameters t_a and t_u. Since prices are just transfers from advertisers to platforms they do not affect welfare.[32]

[30]Note that p^o has to be sufficiently small such that the advertiser market remains fully covered. The upper bound on p^o is then obtained from the participation constraint of the indifferent advertiser at $a = 1/2$ such that $\pi_i(1/2) \geq 0 \leftrightarrow p^o \leq 1 - t_a/\tau(d^o) < 1$.

[31]For very low transportation cost parameters and sufficiently high net benefits $\tau(\cdot) - \nu(\cdot)$ on the platform it might be efficient from a welfare perspective to shut one platform down and let the entire market be served by the other platform due to high network effects. In this case the very fact of having a competing platform is an inefficiency. While this corner solution exhibits an interesting property of platform markets, it is not the focus of this paper and we therefore stick to the case where we have an interior, i.e. duopoly solution as the efficient benchmark.

[32]The same data level d^o would result if we only choose d_i to maximize welfare, while anticipating firms setting ad prices p_i subsequently. These prices would be identical to the prices in the market outcome, given by equation (2.13). The same argument applies for the user optimal level d^u.

2.4.3 User-optimal outcome

Let us now turn to the user-optimal level of data provision. If users are free to decide on the amount of data provided, the user-optimal level d^u is derived from consumer surplus, which is identical to the first two terms in equation (2.6), anticipating second stage market shares as in 2.4.1.[33]

Proposition 2.2 *User utility is maximized by the unique symmetric solution* $(d^u, p^u) = (d_i^u, p_i^u)$ *for* $i \in \{1, 2\}$, *where* d^u *is characterized by*

$$\kappa'(d^u) = -\frac{1}{2}\,\nu'(d^u), \tag{2.8}$$

while the price p^u *can be freely chosen to split the rent between advertisers and platforms, resulting in equal advertiser and user market shares, i.e.* $A_i^u = 1/2$ *and* $X_i^u = 1/2$. [34]

Intuitively, the user-optimal data level balances privacy costs and reduced nuisance benefits for users, at the margin. Note that for constant nuisance costs we get the corner-solution where users would not provide any private data, i.e. $d^u = 0$. For general decreasing nuisance costs, users would be willing to provide a positive level of data $d^u > 0$.

2.4.4 Market outcome

For the market outcome, in the first stage platforms maximize their profits, anticipating second stage market shares as in section 2.4.1.

$$\max_{p_i, d_i} \Pi_i\,(d_i, p_i) = A_i\,\tau(d_i)\,p_i\,X_i \;\forall i \in \{1, 2\} \tag{2.9}$$

We obtain solutions for prices and data levels from the first-order conditions, i.e.

$$\frac{\tau'(d_i)}{\tau(d_i)} = -\frac{\frac{\partial A_i}{\partial d_i} X_i + \frac{\partial X_i}{\partial d_i} A_i}{A_i\,X_i}, \tag{2.10}$$

$$p_i = \frac{A_i\,X_i}{\frac{\partial A_i}{\partial p_i} X_i + \frac{\partial X_i}{\partial p_i} A_i}. \tag{2.11}$$

Intuitively, targeting benefits of data collection must equal the effects on user and advertiser shares, at the margin. Similarly, also prices must reflect their impact on user and advertiser shares. Regarding the curvature of the maximization problem we note that the solution to the first-order conditions represents a maximum as long as the targeting technology $\tau(\cdot)$ is sufficiently concave, the nuisance cost $\nu(\cdot)$

[33] See footnote 32.

[34] Note that p^u has to be sufficiently small such that the advertiser market remains fully covered. The upper bound on p^u can be obtained as outlined in footnote 30.

is sufficiently convex, or both. The details of this condition are given in Appendix 2.A.2.

Proposition 2.3 *There exists a (symmetric) Subgame Perfect Nash Equilibrium with* $(d_i^*, p_i^*) = (d^*, p^*)$ *for* $i \in \{1, 2\}$*, such that the level of data collected from a users is implicitly given by*

$$\kappa'(d^*) = \left(\frac{\nu(d^*) + t_u}{\tau(d^*) - t_a}\right) \frac{\tau'(d^*)}{2} - \frac{\nu'(d^*)}{2} \tag{2.12}$$

and prices per advertisement are

$$p^* = 2\frac{t_a t_u + \nu(d^*)\tau(d^*)}{\tau(d^*)\left[t_u + \nu(d^*)\right]}, \tag{2.13}$$

resulting in equal advertiser and user market shares, i.e. $A_i^* = 1/2$ *and* $X_i^* = 1/2$*.*

Comparing the market level of data provision d^* in (2.12) to the efficient level d^o in (2.7) we see that the marginal targeting benefit $\frac{\tau'(d^*)}{2}$ is additionally weighted by $\frac{\nu(d^*)+t_u}{\tau(d^*)-t_a}$. This distortion is analzyed in detail in chapter 2.6. Note that the equilibrium price p^* does not exceed one and that profits are positive for all advertisers due to Assumption 2.1.[35]

Before we continue we state a corollary concerning the equilibrium effect of data provision on user utility.

Corollary 2.1 *In equilibrium,* $\kappa'(d^*) > -\nu'(d^*)/2$*.*

Proof. See Appendix. □

Intuitively, Corollary 2.1 implies that in equilibrium users' data provision is such that the (negative) privacy costs effect on user utility is larger than the (positive) effect of reduced nuisance. Consequently, in the market outcome too much personal data is provided compared to the user-optimal level.[36]

2.5 Comparative statics

In this section we want to provide economic intuition for the equilibrium results of our model. For this we will provide comparative statics, given changes in advertiser-side competition intensity t_a and user-side competition intensity t_u as well as nuisance $\nu(d)$ and targeting $\tau(d)$ on equilibrium values of personal data provision d^*, ad-per-click price p^*, as well as platform profits Π_i^*, advertiser profits π_i^* and user utility u_i^*.

[35] In Appendix 2.A.2 we provide the details for this result.

[36] In section 2.6 we provide a detailed comparison of the market outcome and the user-optimal outcome.

As most of the comparative statics effects are in line with standard intuition from two-sided platforms, we delegate these analyses to the Online Appendix 2.B and refer to the table in Figure 2.1 for an overview of all derived comparative statics results. In this section we focus on the important and seemingly counter-intuitive effects of competition intensities of both market side.

FIGURE 2.1: Overview of comparative statics

z	$\mathrm{d}d^*/\mathrm{d}z$	$\mathrm{d}p^*/\mathrm{d}z$	$\mathrm{d}\Pi_i^*/\mathrm{d}z$	$\mathrm{d}\pi_i^*/\mathrm{d}z$	$\mathrm{d}u_i^*/\mathrm{d}z$
t_a	$+$	$+$	$+$	$-$	$-$
t_u	$+$	$-$	$-$	$+$	$-$
$\nu(d)$	$+$	$+$	$+$	$-$	$-$
$\tau(d)$	$-$	?	$+$	?	$+$

Note that we distinguish between the platform competition intensity on the user side and on the advertiser side. As platforms are horizontally differentiated vis-à-vis both market sides, competition intensity on each side can be measured through the corresponding transportation cost parameter: higher transportation costs mean higher platform differentiation and thus higher switching costs on this market side, which can be interpreted as more platform market power and hence lower competition intensity.

2.5.1 Advertiser-side competition

First, we consider the effects of advertiser-side competition on data collection. For this consider the platform's first-order condition in equation (2.10) and note that the data level choice depends on the effects of d_i on advertiser and user market shares A_i and X_i. Regarding market share reactions we obtain $\partial X_i/\partial d_i < 0$ and $\partial A_i/\partial d_i < 0$ at equilibrium values.[37] Intuitively, additional data provision d_i would shy away users X_i because marginal privacy costs are higher than marginal benefits of reduced nuisance (compare Corollary 2.1). Although more data provision increases targeting, overall, advertisers would still be repelled by additional data provision because of the detrimental effect on user market share at that platform.

In equilibrium, if competition for advertisers softens, i.e. transportation costs t_a increase, advertisers become 'more sticky', i.e. less sensitive to changes in data provision (and hence user demand) such that $\partial^2 A_i/(\partial d_i \partial t_a) > 0$. Contrary, users become more sensitive to data provision such that $\partial^2 X_i/(\partial d_i \partial t_a) < 0$. Overall, the former effect dominates the latter effect in magnitude. Consequently, and recalling $X_i^* = A_i^* = 1/2$, the right-hand-side of equation (2.10) decreases in t_a such that the equilibrium level of data provision must increase as the left-hand-side is falling in d_i, i.e.

$$\frac{\mathrm{d}d^*}{\mathrm{d}t_a} > 0. \tag{2.14}$$

[37] Derivations can be found in Appendix 2.A.2.

This effect might seem counter-intuitive initially. However note that in equilibrium platforms balance the following trade-off for the data level. On the one hand, more data collection yields higher targeting rates, higher advertiser demand and in sum higher profits. On the other hand, collecting more data decreases user demand, which in turn repels advertisers and thus decreases platform profits. If competition for advertisers softens, the latter effect is dampened more than the former effect is strengthened. This yields a new balance of the trade-off, where more user data is collected.

While advertiser prices p^* rise in t_a (compare Online Appendix 2.B), the effect on user data collection d^* does not follow 'standard' two-sided platform logic as here less competition for advertisers, i.e. less sensitive advertiser demand, *increases* users' data 'payment'. Therefore, users actually benefit from increased competition on the advertiser side, such that also $\mathrm{d}u_i^*/\mathrm{d}t_a < 0$, as discussed in the Online Appendix 2.B. Also, since $\mathrm{d}d^*/\mathrm{d}t_a > 0$ and $\mathrm{d}p^*/\mathrm{d}t_a > 0$ we naturally have $\mathrm{d}\Pi_i^*/\mathrm{d}t_a > 0$.

2.5.2 User-side competition

Second, we evaluate the effects of user-side competition intensity on data collection. Similar to the analysis above, we know that $\partial X_i/\partial d_i < 0$ and $\partial A_i/\partial d_i < 0$ in equilibrium. If competition for users softens, i.e. transportation costs t_u increase, on the one side users become less sensitive to changes in data provision such that $\partial^2 X_i/(\partial d_i \partial t_u) > 0$. Therefore, advertisers also become less sensitive to data provision such that $\partial^2 A_i/(\partial d_i \partial t_u) > 0$ because they care about the share of users on that platforms. Therefore the right-hand-side of equation (2.10) decreases in t_u such that the equilibrium level of data provision must increase, i.e.

$$\frac{\mathrm{d}d^*}{\mathrm{d}t_u} > 0. \tag{2.15}$$

Two effects are intuitively relevant here. On the one hand, platforms care about the share of users on their platform because it increases their profits directly, but also indirectly through more attracted advertisers. On the other hand, platforms want to increase the level of user data collected as it enhances targeting, attracts advertisers and hence increases profits. In equilibrium, stronger competition for users impacts the former effect of attracting users more than the latter of increasing targeting, therefore, platforms will collect less user data. Following the same intuition, platforms would be willing to lose some advertisers in order to not repel valuable users. Hence, also equilibrium advertiser prices increase in t_u (compare Online Appendix 2.B). Contrary to the effects of advertiser-side competition, these results reflect the 'standard' two-sided platform logic: stronger competition for users reduces the 'price' on the user side, while it increases the price on the advertiser side.

Furthermore, we discuss the effect of user-side competition intensity on platform profits. One could expect that platforms' profit increases if competition for users becomes less intense, however the opposite is true. For this note that their profit function in equilibrium is $\Pi_i^* = p^*\tau(d^*)\, A_i^*\, X_i^* = (1/4)\, p^*\tau(d^*)$. Then, a change in user-side competition intensity t_u gives

$$\frac{\mathrm{d}\Pi_i^*}{\mathrm{d}t_u} = \frac{1}{4}\left[\frac{\mathrm{d}p^*}{\mathrm{d}t_u}\tau(d^*) + \tau'(d^*)\frac{\mathrm{d}d^*}{\mathrm{d}t_u}p^*\right]. \tag{2.16}$$

On the one hand, advertiser prices decrease if competition for users becomes less intense (t_u increases), which reduces platform profits. Hence the first term on the right-hand side of (2.16) is negative. On the other hand, the second term is positive, because when competition for users becomes less intense (t_u increases), more data can be collected from users, which leads to more effective ad targeting and therefore increased platform profits. As can be seen from the derivation in Appendix 2.A.2, overall, the negative first-term effect is stronger in equilibrium, such that platforms suffer from weaker competition for users, i.e. $\mathrm{d}\Pi_i^*/\mathrm{d}t_u < 0$.

2.6 Policy implications

In this section we draw comparisons between the different outcomes outlined in section 2.4 and present policy implications.

2.6.1 Comparison of outcomes

First, we want to compare the outcome of the efficiency benchmark with the market equilibrium outcome. If we compare the right-hand-side of the competitive level d^* in (2.12) and the efficient level d^o in (2.7) we can see that the difference will crucially depend on the distortion induced by

$$\delta(d^*) := \frac{\nu(d^*) + t_u}{\tau(d^*) - t_a}, \tag{2.17}$$

which gives more or less weight to the marginal benefit on the advertiser market side $\tau'(d^*)/2$. Note that by Assumption 2.1 the denominator of $\delta(d^*)$ is positive, such that we have $\delta(d^*) > 0$. As the efficient level d^o does not depend on parameter values, we can see that there can be underprovision ($d_u^* < d^o$) as well as overprovision ($d_o^* > d^o$) of personal data in the competitive equilibrium. Depending on the structure of the market too much or too little weight is put on the advertiser side of the market. In particular we can infer from equations (2.12) and (2.7) that the competitive outcome leads to underprovision of personal data if $\delta(d^*) < 1$ and to overprovision if $\delta(d^*) > 1$. Note for $\delta(d^*) = 1$ expression (2.12) simplifies to (2.7), the efficient level of data provision. Using our definition of $\delta(d^*)$ we can then see that $d^* < d^o$ if

$$\delta(d^*) < 1 \quad \Longleftrightarrow \quad \tau(d^*) - \nu(d^*) > t_a + t_u \tag{2.18}$$

and $d^* > d^o$ if

$$\delta(d^*) > 1 \iff \tau(d^*) - \nu(d^*) < t_a + t_u. \tag{2.19}$$

These results are summarized in the following proposition.

Proposition 2.4 *The competitive outcome leads to overprovision of personal data if competition on both market sides is weak and/or if net cross-group externalities are small. If competition on both market sides is strong and/or net cross-group externalities are large, the competitive outcome exhibits underprovision of personal data.*

Proof. See Appendix. □

We want to interpret this finding by first holding the functions $\kappa(d)$, $\nu(d)$ and $\tau(d)$ fixed and asking the question which competitive environment leads to which scenario. From our comparative statics results we know that the amount of data is a monotone function of the transportation cost parameters, i.e. $\frac{\mathrm{d}d^*}{\mathrm{d}t_u} > 0$ and $\frac{\mathrm{d}d^*}{\mathrm{d}t_a} > 0$. Proposition 2.4 then gives us a threshold for how the resulting level of data collection compares to the efficient benchmark: if competition is too strong, i.e. $t_a + t_u$ is small, platforms tend to collect and process an inefficiently small amount of data as users and advertisers shy away too easily. If in turn competition on both sides is weak, i.e. $t_a + t_u$ is high, the market sides become more sticky and platforms are able to extract high amounts of personal data.

We can also hold the competitive environment t_a, t_u on both sides fixed and analyze the effects of relatively strong or weak opposing cross-group externalities. On the one hand, an additional user imposes a positive externality on advertisers (and platforms), which is equal to the targeting effect $\tau(d^*)$. On the other hand, an additional advertiser imposes a negative externality on users, which is equal to the nuisance costs $-\nu(d^*)$. The net effect can therefore be interpreted as available gains from trade in this economy. If the net effect is relatively large, there are significant gains of trade which could be seized by increasing the amount of data collected. If the net effect is small, the gains from trade could be increasd by lowering the amount of collected data.

Comparing the user-optimal level d^u to the welfare-optimal level d^o we immediately see that users would provide an inefficiently low level of data. This result is summarized in the following proposition.

Proposition 2.5 *The user-optimal level of data provision is inefficiently low.*

The reason for this result is straightforward. As users do not internalize the effect the data has on the advertiser market, they will provide data up to the point where the marginal decrease in nuisance equals marginal cost of data provision. Since from a welfare perspective the value creation aspect on the advertiser market is omitted, the resulting level of data provision is inefficiently low. Furthermore, since $\delta(d^*) > 0$ we also have $d^* > d^u$ for all exogenous parameters and functional forms, as shown in Corollary 2.1. Unlike users, platforms act as intermediaries and are able to internalize parts of the value creation on both sides of the market.

2.6.2 Policy conclusions

In this subsection we briefly discuss what conclusions can be drawn from our previous analyses when it comes to policy implications and regulation.

In our model, an omnipotent regulator could obviously achieve the first-best outcome by forcing $d_i = d_j = d^o$ and increasing competition on both sides of the market such that $t_u \to 0$ and $t_a \to 0$. In this case the efficient amount of data is provided while the total transportation costs approach zero.

In practice, regulation and policy discussions typically focus on data and privacy regulation or on competition policy measures (or merger regulation) to assure competitiveness on the user side, for example in the recent Facebook case at the BKartA or the Facebook/Whatsapp merger case in the US and the EU. In this section we want to present answers our model provides for privacy and competition policy, taking into account both market sides and at the same time the effect on privacy.

Privacy regulation

Holding the competitive structure of the market fixed, the regulator could improve upon the market outcome by enforcing the efficient level of private data provision $d_i = d_j = d^o$. However, a direct regulation of the amount of data in our model requires knowledge of the cross-group externalities, i.e. functions $\tau(d)$ and $\nu(d)$, as well as users' privacy concerns $\kappa(d)$.

A regulator could also consider switching to a consumer standard and let consumer freely choose how much data they would like to provide. Our results show that the user-optimal amount of data is always inefficiently low as users do not internalize the benefit on the advertiser side. In particular our results suggest that we can only improve in terms of welfare by switching to a consumer standard when there is extreme overprovision of data in the economy, i.e. platforms have significant market power on both sides of the market. If the market exhibits underprovision, switching to the consumer standard always reduces welfare.

Competition policy

An approach which is less demanding when it comes to information requirements is the regulation of the competitive environment on both market sides, i.e. t_u and t_a.

Our results (Proposition 2.4) suggest that if competition is very weak on both sides ($t_u + t_a$ high), the amount of data collected is likely to be inefficiently high. Similarly, if competition is too strong ($t_u + t_a$ low), too little data is provided from a welfare point of view. While regulators still have to know whether there is overprovision or underprovision in the market in the first place, our results can still provide some guidance.

Our comparative statics results suggest that increasing competition works in the same direction for both sides of the market. The equilibrium amount of data provision is a monotone function of the transportation cost parameters t_a and t_u and by altering either one of the parameters it is possible to push the competitive equilibrium amount of data d^* towards the welfare optimum d^o. Typical examples include reducing switching costs on the user side (see e.g. GDPR/data portability in the EU) or policing vertical integration on the advertiser side (see e.g. debate around Google/DoubleClick acquisition). Further, our results suggest that more competition between platforms is not necessarily welfare enhancing as it further limits the ability to create economic value through the collection of personal data in the case of underprovision.

Also, our results suggest that policy measures, although they work in the same direction, are not equally effective across market sides, i.e. $\frac{\mathrm{d}d^*}{\mathrm{d}t_a} \neq \frac{\mathrm{d}d^*}{\mathrm{d}t_u}$. This might be particularly important in a scenario where the market exhibits underprovision and a regulator would have to reduce competition as this implies increasing transportation costs in the economy. Increasing transportation costs would then lead to more data collection in the subsequent market outcome. Whether we can increase total welfare by increasing transportation costs, however, depends crucially on whether the benefit of higher and thus more efficient data provision (non linear) exceeds the increased costs of transportation (linear).[38] This trade-off could call for a second-best regulation, where competition intensity is regulated in such a way that the amount of data provided in the subsequent market outcome balances the above mentioned benefits and costs at the margin.

From these results on competition policy we want to draw two main conclusions. First, regulating competition on either or both market sides can address the privacy and data collection distortion in the market outcome. Second, whenever regulators consider competition policy or merger regulation in these data-driven indsutries, they should take into account the impact on data collection in the market.

[38] Note that also in a situation of overprovision, the market structure might be such that it is socially beneficial to decrease transportation costs, i.e. increase competition, even beyond the level where it induces efficient data provision (as established in equation 2.7), such that the benefits of decreased transportation costs outweigh the costs from data underprovision.

2.7 Discussion

In this chapter we sketch and briefly discuss extensions and variations of the baseline model presented in Section 2.3.

2.7.1 User prices

In this section we consider an alternative setup where platforms can charge prices on the user side of the market. All other model specifications remain as before, i.e. specifically users now have to pay a monetary price additional to their personal data 'payment'. In a sense, this setup could be considered as an unrestricted model, where platforms are not restricted to zero user prices. Let p_i^u denote the price a user has to pay to join platform i. User utility is then given by

$$u_i(x) = \underline{u} - \kappa(d_i) - \nu(d_i)A_i - p_i^u - t_c|l_i - x|, \tag{2.20}$$

while advertisers still face the same decision as in Section 2.3. Market shares are obtained as before by pinning down indifferent users and advertisers and solving the resulting system of equations. The resulting profit maximization problem of platform i is then given by

$$\max_{p_i, d_i, p_i^c} = A_i \tau(d_i) p_i X_i + p_i^u X_i \;\forall i \in \{1, 2\}. \tag{2.21}$$

Following the same procedure as in our baseline model we obtain symmetric equilibrium values $p_i = p_j = \tilde{p}$, $p_i^u = p_j^u = \tilde{p}^u$ and $d_i = d_j = \tilde{d}$ where advertiser prices are given by $\tilde{p} = 2[t_a + \nu(\tilde{d})]/\tau(\tilde{d})$, user prices by

$$\tilde{p}^u = t_a + t_c + \nu(\tilde{d}) - \tau(\tilde{d}), \tag{2.22}$$

while the equilibrium amount of data is given by

$$\kappa'(\tilde{d}) = \frac{1}{2}\left[\tau'(\tilde{d}) - \nu'(\tilde{d})\right]. \tag{2.23}$$

We immediately see from equations (2.7) and (2.23) that $\tilde{d} = d^o$.

Proposition 2.6 *If platforms can charge prices on both market sides, the efficient level of data is collected.*

Since platforms can now extract rents from both sides of the market, they maximize the aggregate value, whereas in our baseline model platforms only profited on the advertiser side of the market and hence set a data requirement level which is distorted. Taking a closer look at equilibrium user prices in (2.22) we immediately see that negative, positive or zero user prices are possible, depending on parameter values and functional forms.

Proposition 2.7 *If user prices in the two-sided pricing model are positive, the one-sided pricing constraint would result in data overprovision. Contrary, if user prices are negative, this constraint would yield underprovision.*

Proof. See Appendix. □

The intuition for this result is that now platforms can extract the efficient amount of data by adequately compensating users. If net benefits of data collection are large or competition is rather strong, platforms can extract large amounts of data from users and then compensate them by charging negative user prices, whereas in the one-sided pricing model platforms do not have the instrument for compensation and therefore are forced to collect less data than the efficient level. Vice versa, if net benefits are small or competition rather weak, platforms are not forced to monetize through ads by extracting an inefficiently high amount of data, but can obtain positive revenue from the user side instead and leave the amount of data at the efficient level.

We would like to mention at this point that this result may depend on the fact that even with positive user prices we assume the user market to remain fully covered. However, remember that under a market solution with overprovision users gain in terms of utility by decreasing d from d^* to d^o. If this difference in utility is enough to cover the associated positive user price, the user market remains covered. If the consumer price exceeds the utility gain, the two-sided pricing may lead to users leaving the market and efficiency may not be feasible any longer. We provide a more detailed discussion of the full market coverage assumption in the subsequent section. A similar argument can also be made if we consider heterogeneous users as then our uniform pricing setup may not be sufficient to ensure efficiency but platforms would need to engage in price discrimination.

Nevertheless, we would like to draw two further conclusions from these results. Firstly, observing a user price $\tilde{p}^u = 0$ empirically is consistent with the equilibrium result above as well as with our baseline model. By observing zero prices we can not infer whether a price of zero is an optimal choice, making the model above the 'correct' model, or whether there are constraints which prevent platforms from setting user prices at all, making our baseline model more suitable. Secondly, since user prices depend on parameters of competition intensity and externalities, observing zero prices across different markets, jurisdictions and industry sectors makes it unlikely that $\tilde{p}^u = 0$ is a profit maximizing choice in all cases. This strongly supports the argument made by Waehrer (2015) that user prices are not a (practical) variable of interest in real-world platform maximization problems.

2.7.2 Collusion

Full collusion

Let us consider a collusive game where platforms agree on prices $p_i = p_j = p$ and data requirements $d_i = d_j = d$ such that joint profits are maximized. Since advertisers face transportation costs, the profit maximizing collusive price is such that the participation constraint of the indifferent advertiser is binding $\pi_i(1/2) = 0$ which yields $p = 1 - t_a/\tau(d)$. Plugging the collusive price p into the platforms' profit functions (2.3) we obtain $\Pi_i = (\tau(d) - t_a)/4$ and immediately see that profits are increasing in d up to the point where the participation constraint of the indifferent user binds $d : u_i(1/2) = 0$. Since we assumed $\underline{u}$ to be high enough to have interior solutions in the previous sections, we can infer that the collusive amount of data will be excessively high.

Partial collusion

In this section we consider an alternative collusive environment where platforms coordinate on setting a symmetric level of data d but still compete in prices on the advertiser market. The idea is that platforms might influence privacy regulation in a collusive effort without coordinating their pricing decisions. We therefore introduce a collusive stage where platforms agree on a symmetric level d prior to the price setting decision. It is easy to verify that symmetric prices are then given by $p_i = p_j = p(d) \equiv 2\left(t_a t_u + \nu(d)\tau(d)\right) / \left(\tau(d)\left[t_u + \nu(d)\right]\right)$, similar to the market outcome outlined in section 2.4. The key difference, however, is the collusive choice of d. As prices (and d) are symmetric, market shares can be anticipated to be given by $A_i = A_j = X_i = X_j = 1/2$ such that industry wide platform profits are given by $\Pi(d) := \Pi_i(d) + \Pi_j(d) = \tau(d)p(d)/2$.

If we have $\Pi'(d) > 0$ for all d, the collusive level will be the same as in full collusion case, such that the participation constraint of the users will be binding, and if $\Pi'(d) = 0$ has a solution, a possible interior solution exists. The comparison to the market outcome (or to the efficient outcome) is in this case, however, ambiguous and depends on functional forms and parameter values.

Interestingly, industry profits are not necessarily increasing in d. In fact if $\Pi'(d) = p(d)\tau'(d) + p'(d)\tau(d) < 0$ for all d then the collusive level of data will be zero. The reason for this seemingly counter-intuitive result is that increasing d can effectively propagate competition on the advertiser market. In particular if we go back to the definition of advertiser market shares in (2.5) we can see that increasing a symmetric level d has the same effect on the advertiser market as a decrease in transportation costs in the sense that it makes advertisers more reactive towards changes in prices. The intuition is straightforward: if the click-probability is very high, small differences in prices become magnified. The trade-off faced by the platforms is then the following.

An increase in click probability (through increasing d) results in tighter competition on the ad market (depressing p). The optimal d can therefore vary widely depeneding on which effect dominates.

To briefly summarize this section we can conclude that full collusion amongst platforms should be avoided whenever possible. When it comes to partial collusion, however, a more nuanced analysis is necessary as competition on the ad market might be sufficiently strong to prevent inefficient regulatory capture.

2.7.3 Market coverage and multi-homing

In this section we want to briefly discuss the effects of relaxing the assumptions guaranteeing full market coverage and single-homing. We consider market-coverage and multi-homing together because without these assumptions in both cases the market share of a platform is determined by the user/advertiser who is indifferent between joining a platform and the outside option, whereas in the baseline model it was determined by the user/advertiser who is indifferent between joining both platforms. Note that this changes the interpretation of transportation costs in the model substantially. While in the baseline model transportation costs measured a restriction to switching to the other platform and hence a degree of platform competition, now they rather exhibit a restraint on a platform's demand, independent of the other platform. Essentially, lower transportation costs can now be interpreted as *more* elastic demand, whereas in the baseline model they reflected *less* elastic (sticky) demand. While our assumptions for the baseline model were chosen to study full competition between platforms, relaxing the assumptions on one market side significantly changes the setting in the sense that platforms now only compete indirectly through the other market side. Nevertheless, we want to provide some intuition for the robustness of our results. For a more detailed analysis consider the Online Appendix 2.B.

Advertiser side

On the advertiser side, lifting Assumption 2.1 of a covered market together with the single-homing assumption can result in two cases, depending on parameters. First, if transportation costs t_a are sufficiently small, some advertisers 'in the middle' will use both platform (multi-homing). The comparison of the new equilibrium level of data provision to the new efficient level or the baseline level of data provision is, however, ambiguous. This is because less advertiser demand elasticity on the one hand could allow firms to readjust d, while at the same time the total number of advertisers on a platform could rise. From an efficiency perspective, though, more data should be collected than was efficient in the baseline model. Second, if transportation costs t_a are sufficiently high, some advertisers in the middle might choose not to use any platform (no full market coverage). Then it would also be efficient to exclude some advertisers such that the new efficient level of data provision is below the efficient baseline level. The comparison to the equilibrium outcomes remains however ambiguous, as above.

User side

On the user side, relaxing the full-market Assumption 2.2 and the single-homing constraint similarly leads to either some users 'in the middle' joining both platforms (multi-homing) or some user joining neither platform (no full market coverage), depending mainly on transportation costs t_u. In both cases user demand is then merely scaled by the demand elasticity, i.e. the transportation costs t_u, and users' role essentially reduces to being a resource of data needed to create advertising surplus.[39] We find that there would always be over-provision of user data in equilibrium because the efficient benchmark takes into account the trade-off between total value creation and user exclusion, whereas the market outcome only balances targeting benefits and potential user exclusion. However, still less data is collected than in the baseline model and also the efficient level of data decreases. Further, we find that now the transportation costs parameters have no effect on the equilibrium level of data provision. This is because t_u merely scales demand while the relevant trade-off for the choice of d involves the actual utility when joining the platform and is not influenced by the demand scale. Furthermore, equilibrium prices now increase in t_u and decrease in t_a. Because of the reversed role transportation costs now play, this is not contradictory to the baseline model results: the harder it is to keep users, the higher the price for advertisers. Consequently, platform profits still increase and advertiser profits still decrease in user-side elasticity.

2.7.4 Positive cross-group externalities

In the baseline model we considered the case where users incur nuisance cost from seeing ads on the platform, i.e. a negative cross-group externality incured by users. As explained in the beginning we consider this case because we think it illustrates the main results in a very intuitive way. What we demonstrate in the Online Appendix 2.B is that the model can in fact be generalized to have positive cross-group effects in both directions while the major results remain unchanged.

2.8 Conclusion

We analyze the role of competition intensity in a two-sided market framework where platforms collect data from users and monetize through ad-sales. Our model predicts that the equilibrium amount of collected data will be distorted compared to the welfare efficient benchmark. Depending on the net effect of cross-group externalities and the competition intensity on both sides of the market, the distortion can lead

[39] Note that on the advertiser side this was not the case because advertisers pay money rather than a value-creating resource.

to underprovision or overprovision of personal data. Since the level of collected data increases the more market power platforms have on either side of the market, side specific regulations are substitutable. We also show that a consumer standard would always lead to underprovision of data as users do not internalize improvements in the targeting capabilities. Lastly, we showed that two-sided pricing induces platforms to choose the efficient level of data by adequately compensating users.

While we think our model provides useful insights we would also like to discuss some limitations. It would be interesting to further explore the role of multi-homing on the advertiser side as it changes the competitive dynamics substantially. Secondly, one could alter the setting on the user side and consider heterogeneous users, while platforms engage in second degree discrimination by offering a menu of data choices. We think those are interesting avenues for future research.

2.A Appendix

2.A.1 Omitted analysis

Second stage market shares

Note that equations (2.4) - (2.5) are consistent, non-redundant and linear in X_i,X_j,A_i and A_j such that the resulting solution in (2.4.1) is unique. Explicit market shares are then given by:

$$
\begin{aligned}
X_i &= \frac{t_a(2\kappa(d_j) - 2\kappa(d_i) + \nu(d_j) - \nu(d_i) + 2t_u) + (1-p_j)\tau(d_j)(\nu(d_i) + \nu(d_j))}{4t_a t_u + (\nu(d_i) + \nu(d_j))((1-p_i)\tau(d_i) + (1-p_j)\tau(d_j))} \\
X_j &= \frac{t_a(2\kappa(d_i) - 2\kappa(d_j) + \nu(d_i) - \nu(d_j) + 2t_u) + (1-p_i)\tau(d_i)(\nu(d_i) + \nu(d_j))}{4t_a t_u + (\nu(d_i) + \nu(d_j))((1-p_i)\tau(d_i) + (1-p_j)\tau(d_j))} \\
A_i &= \frac{(1-p_i)\tau(d_i)(\kappa(d_j) - \kappa(d_i) + \nu(d_j) + t_u) - (1-p_j)\tau(d_j)(\kappa(d_i) - \kappa(d_j) - \nu(d_j) + t_u) + 2t_a t_u}{4t_a t_u + (\nu(d_i) + \nu(d_j))((1-p_i)\tau(d_i) + (1-p_j)\tau(d_j))} \\
A_j &= 1 \\
&\quad - \frac{(1-p_i)\tau(d_i)(\kappa(d_j) - \kappa(d_i) + \nu(d_j) + t_u) - (1-p_j)\tau(d_j)(\kappa(d_i) - \kappa(d_j) - \nu(d_j) + t_u) + 2t_a t_u}{4t_a t_u + (\nu(d_i) + \nu(d_j))((1-p_i)\tau(d_i) + (1-p_j)\tau(d_j))}
\end{aligned}
$$

Second order conditions

In the following we derive sufficient conditions such that the equilibrium values p^*, d^* derived from the maximization problem presented in section 2.3 characterize a local maximum. Let us consider the Hessian evaluated at equilibrium values. Starting with

$$
\left.\frac{\partial^2 \Pi_i}{\partial p_i^2}\right|_{d^*,p^*} = -\frac{t_u^2\ \tau(d^*)^2(\nu(d^*) + t_u)}{4(t_u - \nu(d^*))^2(\nu(d^*)\tau(d^*) + t_a t_u)}
$$

we immediately see that $\left.\frac{\partial^2 \Pi_i}{\partial p_i^2}\right|_{d^*,p^*} < 0$, a necessary condition for the Hessian to be negative definite. In the next steps we argue that we can always find functions $\tau(\cdot), \nu(\cdot)$ such that $det(H)|_{d^*,p^*} > 0$. First, it is helpful to look at the numerator and the denominator of the Hessian separately

$$det(H)|_{d^*,p^*} = \frac{H_{num}}{H_{den}}$$

where the numerator H_{num} and the denominator H_{den} are given by

$$\begin{aligned}
H_{num} &= \tau(d^*)^2 \Big[-4t_u^2(t_a-\tau(d^*))(\nu(d^*)\tau(d^*)+t_at_u)\left(\nu''(d^*)(t_a-\tau(d^*))+\tau''(d^*)(\nu(d^*)+t_u)\right) \\
&\quad -t_u^2\nu'(d^*)^2(t_a-\tau(d^*))^3-\tau'(d^*)^2(\nu(d^*)+t_u)^2\left(\nu(d^*)(\nu(d^*)(t_a-\tau(d^*))+4t_c\tau(d^*))+4t_at_u^2\right) \\
&\quad +2t_u\nu(d^*)\nu'(d^*)\tau'(d^*)(t_a-\tau(d^*))^2(\nu(d^*)+t_u)\Big] \\
H_{den} &= 64(t_a-\tau(d^*))(t_u-\nu(d^*))^2(\nu(d^*)\tau(d^*)+t_at_u)^2
\end{aligned}$$

Note that $H_{den} < 0$ as we have $(t_a - \tau(d^*)) < 0$ from Assumption 2.1. Rewriting H_{num} as

$$\begin{aligned}
H_{num} &= \tau(d^*)^2\left[H1_{num}\left(H2_{num}\nu''(d^*)+H3_{num}\tau''(d^*)\right)+H4_{num}+H5_{num}+H6_{num}\right] \\
H1_{num} &= -4t_u^2(t_a-\tau(d^*))(\nu(d^*)\tau(d^*)+t_at_u) > 0 \\
H2_{num} &= (t_a-\tau(d^*)) < 0 \\
H3_{num} &= (\nu(d^*)+t_u) > 0 \\
H4_{num} &= -t_u^2\nu'(d^*)^2(t_a-\tau(d^*))^3 \geq 0 \\
H5_{num} &= -\tau'(d^*)^2(\nu(d^*)+t_u)^2\left(\nu(d^*)(\nu(d^*)(t_a-\tau(d^*))+4t_u\tau(d^*))+4t_at_u^2\right) \lesseqgtr 0 \\
H6_{num} &= 2t_u\nu(d^*)\nu'(d^*)\tau'(d^*)(t_a-\tau(d^*))^2(\nu(d^*)+t_u) \leq 0
\end{aligned}$$

we can see that requiring $H_{num} < 0$ is equivalent to the condition

$$-\frac{1}{H1_{num}}\left(H4_{num}+H5_{num}+H6_{num}\right) > H2_{num}\nu''(d^*)+H3_{num}\tau''(d^*)$$

where $LHS \lesseqgtr 0$ while $RHS < 0$ due to our functional requirements on $\tau(\cdot)$ and $\nu(\cdot)$. The important thing to realize is that, firstly, the condition for negative definiteness reduces to a condition which is linear in $\nu''(d^*)$ and $\tau''(d^*)$, the curvature information of the targeting and the nuisance functions, and secondly, is given by an upper bound. If the sign of the upper bound is positive then this condition is always fulfilled as we have $RHS < 0$. Only if the sign of the upper bound is negative, the condition may bind. But then we can assume that $\tau(\cdot)$ is sufficiently concave and/or $\nu(\cdot)$ is sufficiently convex such that this condition holds since for our results we only require $\tau''(\cdot) < 0$ and $\nu''(\cdot) \geq 0$ which is in line with this condition.

Market outcome

In equilibrium $p^* < 1$ and $\pi_i^*(a) \geq 0$. To see this note that given equation (2.13), $p^* < 1$ if

$$2\frac{t_at_u+\nu(d^*)\tau(d^*)}{\tau(d^*)t_u+\nu(d^*)\tau(d^*)} < 1 \iff t_a < \tau(d^*)\frac{(t_u-\nu(d^*))}{2t_u} < \tau(d^*) \tag{2.24}$$

By Assumption 2.1 we have that $\tau(d) > t_a$ for all d and therefore in particular also $\tau(d^*) > t_a$. Further, we have that $0 < (t_u - \nu(d^*))/2t_u < 1$, hence the last inequality.

Thus, Assumption 2.1 is sufficient for the expression above to hold and $p^* < 1$.

Even the indifferent advertiser with highest transportation costs has positive profits in equilibrium because

$$\pi_i^*(\frac{1}{2}) = \frac{\tau(d^*)}{2} - \frac{t_a t_u + \nu(d^*)\tau(d^*)}{t_u + \nu(d^*)} - \frac{t_a}{2} \geq 0 \iff \tau(d^*)\frac{t_u - \nu(d^*)}{3t_u + \nu(d^*)} \geq t_a, \quad (2.25)$$

which is guaranteed by Assumption 2.1 for all d and especially for d^*. For this note that the term on the left in the last inequality is increasing in d.

2.A.2 Omitted proofs

Proofs of propositions & corollaries

Proof of Corollary 2.1

Proof. Rearranging terms in the first-order condition of platform profit maximization, given by equation (2.12), yields $2\kappa'(d^*) + \nu'(d^*) = \tau'(d^*)\frac{\nu(d^*)+t_u}{\tau(d^*)-t_a}$. By Assumption 2.1 we have $\tau(d^*) > t_a$. Hence the right hand side is positive, such that $2\kappa'(d^*)+\nu'(d^*) > 0$. □

Proof of Proposition 2.4

Proof. The proof relies on the monotonicity of the LHS and RHS in equations (2.7) and (2.12). Suppose, $\delta(d^*) > 1$ but $d^* < d^o$ and hence $\kappa'(d^*) < \kappa'(d^o)$. Using the implicit definition of d^o in (2.7) and d^* in (2.12) this implies $\delta(d^*)\tau'(d^*) - \nu'(d^*) < \tau'(d^o) - \nu'(d^o)$. Rearranging yields $\delta(d^*) < \frac{\tau'(d^o)}{\tau'(d^*)} + \frac{\nu'(d^*)-\nu'(d^o)}{\tau'(d^*)}$. But due to the curvature of $\tau(\cdot), \nu(\cdot)$ we have $\frac{\tau'(d^o)}{\tau'(d^*)} < 1$ and $\frac{\nu'(d^*)-\nu'(d^o)}{\tau'(d^*)} \leq 0$ for $d^* < d^o$, contradicting $\delta(d^*) > 1$. Now suppose $\delta(d^*) > 1$ and $d^* > d^o$, and hence $\delta(d^*) < \frac{\tau'(d^o)}{\tau'(d^*)} + \frac{\nu'(d^*)-\nu'(d^o)}{\tau'(d^*)}$. For $d^* > d^o$ we then have $\frac{\tau'(d^o)}{\tau'(d^*)} > 1$ and $\frac{\nu'(d^*)-\nu'(d^o)}{\tau'(d^*)} \geq 0$ and hence $\delta(d^*) > 1$. □

Proof of Proposition 2.7

Proof. To see that positive user prices in the two-sided model correspond to data overprovision in the one-sided pricing model, note that user prices are positive in the two-sided pricing model if $\tau(d^o) - \nu(d^o) < t_a + t_u$. From Proposition 2.4 we know that in the one-sided pricing model too little data is provided if $t_a + t_u < \tau(d^*) - \nu(d^*)$. But this would mean that $d^* < d^o$, which contradicts $\tau(d^o) - \nu(d^o) < t_a + t_u < \tau(d^*) - \nu(d^*)$, as $\tau(d)$ is increasing and $\nu(d)$ decreasing in d. Hence it can only be that in the one-sided model there is overprovision, such that $d^* > d^o$ and $\tau(d^o) - \nu(d^o) < \tau(d^*) - \nu(d^*) < t_a + t_u$.

To see that negative user prices in the two-sided model correspond to data underprovision in the one-sided pricing model, note that user prices are negative in the two-sided pricing model if $\tau(d^o) - \nu(d^o) > t_a + t_u$. From Proposition 2.4 we know that too much data is provided if $t_a + t_u > \tau(d^*) - \nu(d^*)$. But this would mean that $d^* > d^o$, which contradicts $\tau(d^o) - \nu(d^o) > t_a + t_u > \tau(d^*) - \nu(d^*)$. Hence it must be that in the one-sided model there is underprovision, such that $d^* < d^o$ and $\tau(d^o) - \nu(d^o) > \tau(d^*) - \nu(d^*) > t_a + t_u$. $\square$

Proofs for comparative statics

For the effect of transportation costs t_a and t_u on d_i note first that

$$\left.\frac{\partial X_i}{\partial d_i}\right|_{\substack{d_i=d^*\\p_i=p^*}} = -\frac{\{t_a t_u + \nu(d^*)\left[t_a p^* + (1-p^*)\tau(d^*)\right]\}\,\tau'(d^*)}{4\left[\tau(d^*) - t_a\right]\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]} < 0, \tag{2.26}$$

$$\left.\frac{\partial A_i}{\partial d_i}\right|_{\substack{d_i=d^*\\p_i=p^*}} = -\frac{(1-p^*)\left[t_a t_u + \nu(d^*)\tau(d^*)\right]\tau'(d^*)}{4\left[\tau(d^*) - t_a\right]\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]} < 0, \tag{2.27}$$

because $\tau'(d^*) > 0$, while $\tau(d^*) > t_a$ by Assumption 2.1 and $p^* < 1$ as established in Section 2.A.1. Differentiating (2.26) and (2.27) with respect to transportation costs yields

$$\left.\frac{\partial^2 X_i}{\partial d_i \partial t_a}\right|_{\substack{d_i=d^*\\p_i=p^*}} = -\frac{(1-p^*)\nu(d^*)\left[t_a t_u + \nu(d^*)\tau(d^*)\right]\tau'(d^*)}{4\left[\tau(d^*) - t_a\right]\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]^2} < 0,$$

$$\left.\frac{\partial^2 A_i}{\partial d_i \partial t_a}\right|_{\substack{d_i=d^*\\p_i=p^*}} = \frac{(1-p^*)t_u\left[t_a t_u + \nu(d^*)\tau(d^*)\right]\tau'(d^*)}{4\left[\tau(d^*) - t_a\right]\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]} > 0,$$

$$\left.\frac{\partial^2 X_i}{\partial d_i \partial t_u}\right|_{\substack{d_i=d^*\\p_i=p^*}} = \frac{t_a\{t_a t_u + \nu(d^*)\left[t_a p^* + (1-p^*)\tau(d^*)\right]\}\,\tau'(d^*)}{4\left[\tau(d^*) - t_a\right]\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]} > 0,$$

$$\left.\frac{\partial^2 A_i}{\partial d_i \partial t_u}\right|_{\substack{d_i=d^*\\p_i=p^*}} = \frac{(1-p^*)\tau(d^*)\{t_a t_u + \nu(d^*)\left[t_a p^* + (1-p^*)\tau(d^*)\right]\}\,\tau'(d^*)}{4\left[\tau(d^*) - t_a\right]\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]} > 0.$$

Further note that

$$\frac{\partial^2 A_i}{\partial d_i \partial t_a} - \left.\frac{\partial^2 X_i}{\partial d_i \partial t_a}\right|_{\substack{d_i=d^*\\p_i=p^*}} = \frac{(1-p^*)\left[t_u + \nu(d^*)\right]\left[t_a t_u + \nu(d^*)\right]\tau'(d^*)}{4\left[\tau(d^*) - t_a\right]\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]} > 0.$$

To see that $\mathrm{d}\Pi_i^P/\mathrm{d}t_u < 0$, note that

$$\begin{aligned}
\frac{\mathrm{d}\Pi_i^P}{\mathrm{d}t_u} &= \frac{-\left[\tau(d^*) - t_a\right]\left[\nu(d^*) - t_u\nu'(d^*)\frac{\mathrm{d}d^*}{\mathrm{d}t_u}\right] + \frac{\mathrm{d}d^*}{\mathrm{d}t_u}\nu(d^*)\tau'(d^*)\left[t_u + \nu(d^*)\right]}{\left[t_c + \nu(d^*)\right]^2} \\
&= \frac{\left[\tau(d^*) - t_a\right]^2}{\left[t_u + \nu(d^*)\right]^2 \Psi(d^*)} \left[\left(t_u + \nu(d^*)\right)\nu'(d^*)\tau'(d^*)\right. \\
&\quad \left. - \nu(d^*)\left\{\left(\tau(d^*) - t_a\right)\left[\kappa''(d) + \nu''(d^*)\right] - t_c\left(t_u + \nu(d^*)\right)\tau''(d^*)\right\}\right] \\
&< 0,
\end{aligned}$$

where $\mathrm{d}d^*/\mathrm{d}t_u$ is from equation (2.15), while the term in the denominator is given by

$$\begin{aligned}
\Psi(d^*) = &\left[2\kappa''(d^*) + \nu''(d^*)\right]\left(\tau(d^*) - t_a\right)^2 - \nu'(d^*)\tau'(d^*)\left(\tau(d^*) - t_a\right) \\
&+ \left(\nu(d^*) + t_u\right)\left[\tau'(d^*)^2 - \left(\tau(d^*) - t_a\right)\tau''(d^*)\right] > 0.
\end{aligned} \tag{2.28}$$

Note for the inequalities that $\tau'(d^*) > 0$, $\tau''(d^*) < 0$ while $\nu'(d^*) \leq 0$, $\nu''(d^*) \geq 0$ by construction, and $\tau(d^*) > t_a$ by Assumption 2.1.

2.B Online Appendix

In this online appendix we will provide derivations and intuition for comparative statics not covered in the main text. Further, we present extensions to our baseline model where we consider multi-homing, elastic total demand and positive cross-group externalities.

Comparative static effects on prices in equilibrium

For this analysis consider the platform's first-order condition in equation (2.11) and note that the price depends indirectly on the effects of p_i on advertiser and user market shares A_i and X_i as given in Section 2.4.1.

$$\left.\frac{\partial X_i}{\partial p_i}\right|_{\substack{d_i=d^*\\ p_i=p^*}} = \frac{\nu(d^*)\tau(d^*)}{4\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]} > 0, \tag{2.29}$$

$$\left.\frac{\partial A_i}{\partial p_i}\right|_{\substack{d_i=d^*\\ p_i=p^*}} = -\frac{t_u\tau(d^*)}{4\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]} < 0, \tag{2.30}$$

because $p^* < 1$ as established in Appendix 2.A.2.

Competition for advertisers

Note that in Section 2.5 we discussed that lower advertiser-side competition intensity increases the level of data collection in equilibrium, i.e. $\mathrm{d}d^*/\mathrm{d}t_a > 0$. Here we analyze the effects of competition intensity for advertisers on p^*. Differentiating (2.29) with respect to transportation costs t_a yields

$$\left.\frac{\partial^2 X_i}{\partial p_i \partial t_a}\right|_{\substack{d_i=d^*\\ p_i=p^*}} = -\frac{t_u\tau(d^*)\nu(d^*)}{4\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]^2} < 0,$$

$$\left.\frac{\partial^2 A_i}{\partial p_i \partial t_a}\right|_{\substack{d_i=d^*\\ p_i=p^*}} = \frac{t_u^2\,\tau(d^*)}{4\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]^2} > 0.$$

Further note that

$$\left.\frac{\partial^2 A_i}{\partial p_i \partial t_a} - \frac{\partial^2 X_i}{\partial p_i \partial t_a}\right|_{\substack{d_i=d^*\\ p_i=p^*}} = \frac{t_u\left[t_u + \nu(d^*)\right]\tau(d^*)}{4\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]^2} > 0.$$

If competition for advertisers softens, i.e. transportation costs t_a increase, advertisers become less sensitive to changes in prices such that $\partial^2 A_i/(\partial p_i \partial t_a) > 0$. Consequently, users become more sensitive to prices (which repel advertisers) such that $\partial^2 X_i/(\partial p_i \partial t_a) < 0$. Overall, the former effect dominates the latter effect in magnitude. Consequently, and as $X_i^* = A_i^* = 1/2$, the right-hand-side of equation

(2.11) increases in t_a such that the equilibrium price must rise, i.e.

$$\frac{\mathrm{d}p^*}{\mathrm{d}t_a} > 0. \tag{2.31}$$

Intuitively, higher advertiser transportation costs mean more sticky advertisers and hence decreased platform competition for advertisers. Therefore, it is straightforward that advertiser prices rise, which is line with standard intuition.

Competition for users

In section 2.5 we discussed that lower competition intensity for users decreases platforms' equilibrium level of data collection, i.e. $\mathrm{d}d^*/\mathrm{d}t_u > 0$. Here we analyze the effects of competition intensity for users on p^*. Differentiating (2.29) with respect to transportation costs t_u yields

$$\left.\frac{\partial^2 X_i}{\partial p_i \partial t_u}\right|_{\substack{d_i=d^*\\ p_i=p^*}} = -\frac{t_a \tau(d^*)\nu(d^*)}{4\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]^2} < 0,$$

$$\left.\frac{\partial^2 A_i}{\partial p_i \partial t_u}\right|_{\substack{d_i=d^*\\ p_i=p^*}} = -\frac{(1-p^*)\nu(d^*)\tau(d^*)^2}{4\left[t_a t_u + (1-p^*)\nu(d^*)\tau(d^*)\right]^2} < 0.$$

If competition for users softens, i.e. transportation costs t_u increase, users become less sensitive to changes in prices such that $\partial^2 X_i/(\partial p_i \partial t_u) < 0$. Consequently, advertisers, too, become less sensitive to prices (which now repel less users) such that $\partial^2 X_i/(\partial d_i \partial t_u) < 0$. Therefore the right-hand-side of equation (2.11) decreases in t_u such that the equilibrium price must fall, i.e.

$$\frac{\mathrm{d}p^*}{\mathrm{d}t_u} < 0. \tag{2.32}$$

Again, this is in line with standard platform intuition: advertiser prices fall if the user side becomes less sensitive (elastic).

Nuisance

First, we consider the effects of nuisance on data collection.[40] Totally differentiating the first-order conditions from equations (2.12) and (2.13) w.r.t. $\nu(d)$ and solving for $\mathrm{d}d^*/\mathrm{d}\nu(d)$ yields

[40] Note that nuisance is a function in our model. To assess an increase in nuisance we treat it as fixed and consider an upward shift, without changing any curvature. For this we slightly abuse notation to stay consistent with the rest of our comparative statics, such that e.g. by $\mathrm{d}d^*/\mathrm{d}\nu(d)|_{d=d^*}$ we intuitively consider the effect of adding a positive constant c to the function, i.e. $\nu(d) + c$ where $c > 0$, on d^*.

$$\left.\frac{\mathrm{d}d^*}{\mathrm{d}\nu(d)}\right|_{d=d^*} = \frac{(\tau(d^*) - t_a)\,\tau'(d^*)}{\Psi(d^*)} > 0. \tag{2.33}$$

Second, we evaluate the effects of nuisance on p^*. Solving for $\mathrm{d}p^*/\mathrm{d}\nu(d)$ and dropping the argument d^* of $\nu(d^*)$ and $\tau(d^*)$ to abbreviate, yields

$$\left.\frac{\mathrm{d}p^*}{\mathrm{d}\nu(d)}\right|_{d=d^*} = \frac{-2t_u\,(t_a - \tau)^2\left[\tau\,(\tau''\,(\nu + t_u) - (\tau - t_a)\,(2\kappa'' + \nu'')) - (\nu + t_u)\,\tau'^2\right]}{(\nu + t_u)\,\tau^2\,\Psi(d^*)} > 0, \tag{2.34}$$

where $\Psi(d^*)$ is defined in equation (2.28). Intuitively, higher (absolute) nuisance results in lower user demand. To counterbalance this effect, platforms would increase ad prices as ads become relatively less attractive. Additionally, more user data would be collected in order to soften the nuisance increase. Interpreted from the point of view of users, they are now willing to incur marginally more privacy costs in order to obtain some nuisance reduction.

Targeting

First, we consider the effects of the targeting technology on data collection.[41] Solving for $\mathrm{d}d^*/\mathrm{d}\tau(d)$ yields

$$\left.\frac{\mathrm{d}d^*}{\mathrm{d}\tau(d)}\right|_{d=d^*} = -\frac{(\nu(d^*) + t_u)\,\tau'(d^*)}{\Psi(d^*)} < 0. \tag{2.35}$$

Second, we evaluate the effects of nuisance on p^*. Solving for $\mathrm{d}p^*/\mathrm{d}\tau(d)$ and dropping again the argument d^* to abbreviate, yields

$$\left.\frac{\mathrm{d}p^*}{\mathrm{d}\tau(d)}\right|_{d=d^*} = \frac{2t_u\,(\tau - t_a)\left[\tau''\,(\nu + t_u)\,t_a - (\tau - t_a)\left[\nu'\tau' + t_a\,(2\kappa'' + \nu'')\right]\right]}{(\nu + t_u)\,\tau^2\Psi(d^*)} \gtrless 0. \tag{2.36}$$

platforms to create the same ad value with less personal data, hence in equilibrium platforms will compete to 'relax' the data requirement for users. Two effects are relevant for the effect on ad prices. On the one hand ads become more valuable, hence platforms might increase the price, i.e. their share, of this value (intensive margin). On the other hand, platforms might prefer to attract more of these valuable advertisers by reducing the ad price (extensive margin). Overall, the effect on ad prices depends on which of the opposing effects is stronger.

[41] Note that targeting is a function, which we treat as fixed here, such that comparative statics are performed as described in footnote 40.

Comparative static effects on platform profits, advertiser profits and user utility

In this subsection we provide further intuition on equilibrium profits and utility by presenting comparative statics.

Effects on platform profits

The effects on platform profits $\Pi_i^* = p^*\tau(d^*)\, X_i^*\, A_i^* = (1/4)\, p^*\tau(d^*)$ can be written as

$$\frac{\mathrm{d}\Pi_i^*}{\mathrm{d}z} = \frac{1}{4}\left[\frac{\mathrm{d}p^*}{\mathrm{d}z}\tau(d^*) + \tau'(d^*)\frac{\mathrm{d}d^*}{\mathrm{d}z}p^*\right]. \tag{2.37}$$

We look at the effects of advertiser competition intensity. For $z = t_a$ both terms on the right-hand side are positive and hence $\mathrm{d}\Pi_i^*/\mathrm{d}t_a > 0$. Intuitively, when competition for advertisers becomes more intense (t_a decreases), then prices for ad-placing decrease. In turn, less data is collected from users, such that targeting becomes less effective, and less total revenue is made on the ad market. Both these effects decrease platform profits.

The intensity of user-side competition increases platforms' surplus, i.e. $\mathrm{d}\Pi_i^*/\mathrm{d}t_u < 0$. This effect is discussed in the main text in section 2.5.

Increased nuisance (higher $z = \nu(d)$) increases platforms' surplus, i.e. $\mathrm{d}\Pi_i^*/\mathrm{d}\nu(d) > 0$. More data is collected, which increases targeting and hence the (residual) value of a placed ad, thus also higher prices can be sustained. Overall, this unambiguously benefits platforms.

Increased targeting (higher $z = \tau(d)$) increases platforms' surplus, i.e. $\mathrm{d}\Pi_i^*/\mathrm{d}\tau(d) > 0$. Although less data is collected, the absolute externality of users, i.e. targeting, increases the value to be shared between platforms and advertisers. While the effect on prices remains ambiguous, overall, platforms benefit. To see that note that

$$\begin{aligned}\frac{\mathrm{d}\Pi_i^*}{\mathrm{d}\tau(d)} = {} & \frac{\tau(d^*) - t_a}{(t_u + \nu(d^*))\,\Psi(d^*)}\left[-\left(t_u + \nu(d^*)\right)\nu'(d^*)\tau'(d^*)\right. \\ & \left. + \nu(d^*)\left\{(\tau(d^*) - t_a)\left[\kappa''(d) + \nu''(d^*)\right] - t_c\left(t_u + \nu(d^*)\right)\tau''(d^*)\right\}\right] > 0,\end{aligned} \tag{2.38}$$

where $\mathrm{d}d^*/\mathrm{d}t_u$ is from equation (2.15), while $\Psi(d^*)$ is defined in equation (2.28).

Effects on advertiser profits

The effects on advertiser profits

$$\begin{aligned}\pi_i^*(a) &= (1 - p^*)\,\tau(d^*)\, X_i^* - t_a|l_i - a| \\ &= \frac{1}{2}\,(1 - p^*)\ \tau(d^*) - t_a|l_i - a|\end{aligned}$$

are given by

$$\frac{\mathrm{d}\pi_i^*(a)}{\mathrm{d}z} = \frac{1}{2}\left[-\frac{\mathrm{d}p^*}{\mathrm{d}z}\tau(d^*) + \tau'(d^*)\frac{\mathrm{d}d^*}{\mathrm{d}z}(1-p^*)\right] - |l_i - a|\frac{\mathrm{d}t_a}{\mathrm{d}z}. \tag{2.39}$$

Stronger competition for advertisers (lower $z = t_a$) makes advertisers overall better off, i.e. $\mathrm{d}\pi_i^*/\mathrm{d}t_a < 0$. However, there are multiple effects at work. Firstly, prices fall, such that the first term on the right hand side increases. Secondly, less personal data from users can be collected, which makes targeting less effective, therefore the second term is negative. Thirdly, also transportation costs decrease, which increases advertiser profits. Overall, the price and transportation cost reduction effects outweigh decreased targeting effectiveness. For this note that

$$\begin{aligned}\frac{\mathrm{d}\pi^A}{\mathrm{d}t_a} &= \frac{1}{4\left[t_u+\nu(d^*)\right]^2}\Bigg\{-6t_u\nu(d^*) - \nu(d^*)^2\left[1+2\tau'(d^*)\frac{\mathrm{d}d^*}{\mathrm{d}t_a}\right] \\ &\qquad + t_c\left[-4\nu'(d^*)\frac{\mathrm{d}d^*}{\mathrm{d}t_a}\left(\tau(d^*)-t_a\right) + t_c\left(-5+2\tau'(d^*)\frac{\mathrm{d}d^*}{\mathrm{d}t_a}\right)\right]\Bigg\} \\ &= -\frac{1}{4\left[t_u+\nu(d^*)\right]\Psi(d^*)}\Bigg\{-\nu'(d^*)\left(t_u+\nu(d^*)\right)\left(\tau(d^*)-t_a\right)\tau'(d^*) + 3\left(t_u+\nu(d^*)\right)^2\tau'(d^*)^2 \\ &\qquad - \left(5t_u+\nu(d^*)\right)\left(\tau(d^*)-t_a\right)\left[-\nu''(d^*)\left(\tau(d^*)-t_a\right) + \left(t_u+\nu(d^*)\right)\tau''(d^*)\right]\Bigg\} \\ &< 0, \end{aligned} \tag{2.40}$$

where $\mathrm{d}d^*/\mathrm{d}t_a$ is from equation (2.14), while $\Psi(d^*)$ is defined in equation (2.28).

Stronger competition for users (increase $z = t_u$) hurts advertisers, hence $\mathrm{d}\pi_i^A/\mathrm{d}t_u > 0$. The platforms' bottleneck position allows them to increase prices (negative first term) and, further, less user data can be collected, such that targeting becomes less effective (negative second term).

Increased nuisance (higher $z = \nu(d)$) decreases advertisers' surplus, i.e. $\mathrm{d}\pi_i^A/\mathrm{d}\nu(d) < 0$. Although more data is collected, which increases targeting and hence the value of a placed ad, also prices increase. Overall, this hurts advertisers. To see that, note

$$\begin{aligned}\frac{\mathrm{d}\pi^A}{\mathrm{d}\nu(d)} &= -\frac{\left[\tau(d^*)-t_a\right]}{2\left[t_u+\nu(d^*)\right]^2\Psi(d^*)}\Bigg\{\left(t_u+\nu(d^*)\right)^2\tau'(d^*)^2 \\ &\qquad + 2\left[\tau(d^*)-t_a\right]t_c\left\{\left(\tau(d^*)-t_a\right)\left[\kappa''(d)+\nu''(d^*)\right] - t_c\left(t_u+\nu(d^*)\right)\tau''(d^*)\right\}\Bigg\} \\ &< 0, \end{aligned} \tag{2.41}$$

Increased targeting (higher $z = \tau(d)$) has an ambiguous effect on advertisers' surplus. While the targeting function becomes better, less data needs be collected which again reduces targeting effectiveness. Further, the effect on prices is ambiguous. Hence, overall effects on advertiser surplus remain unclear.

Effects on user utility

The effects on a user's utility $u_i^*(x) = \underline{u} - \kappa(d^*) - \nu(d^*)A_i^* - t_u|l_i - x| = \underline{u} - \kappa(d^*) - (1/2)\,\nu(d^*) - t_u|l_i - x|$ are given by

$$\frac{u_i^*(x)}{\mathrm{d}z} = -\frac{\mathrm{d}d^*}{\mathrm{d}z}\left[\kappa'(d^*) + \frac{\nu'(d^*)}{2}\right] - \frac{\mathrm{d}t_u}{\mathrm{d}z}|l_i - x|. \tag{2.42}$$

Note that by Corollary 2.1 the term in brackets on the right-hand side is positive and that for $z \in \{t_a, t_u\}$ we have $\mathrm{d}d^*/\mathrm{d}z > 0$ such that $\mathrm{d}u_i/\mathrm{d}z < 0$.

Intuitively, less competition for advertisers (higher $z = t_a$) increases the amount of data collected in equilibrium, which overall leaves users worse off, as privacy concerns are increased, although ads are more targeted and hence nuisance smaller.

Less competition for users (higher $z = t_u$) increases the amount of data collected, such that privacy concerns are increased, although it reduces nuisance costs. Further strengthened by increased transportation costs for users, quite naturally users' utility overall decreases.

Increased nuisance (higher $z = \nu(d)$) decreases users' utility, i.e. $\mathrm{d}u_i/\mathrm{d}\nu(d) < 0$ because again more data is collected.

Increased targeting (higher $z = \tau(d)$) increases users' utility, i.e. $\mathrm{d}u_i/\mathrm{d}\tau(d) < 0$. Although targeting does not directly affect users, less data is collected, which is beneficial for users.

Market coverage and multi-homing

Advertiser side

We start this section by lifting Assumption 2.1 for full market coverage and the single-homing assumption for advertisers. Analytically, this is achieved by pinning down advertisers which are indifferent between joining a platform and abstaining such that the total mass of advertisers joining platform i is determined by $\pi_i(a) = 0$.

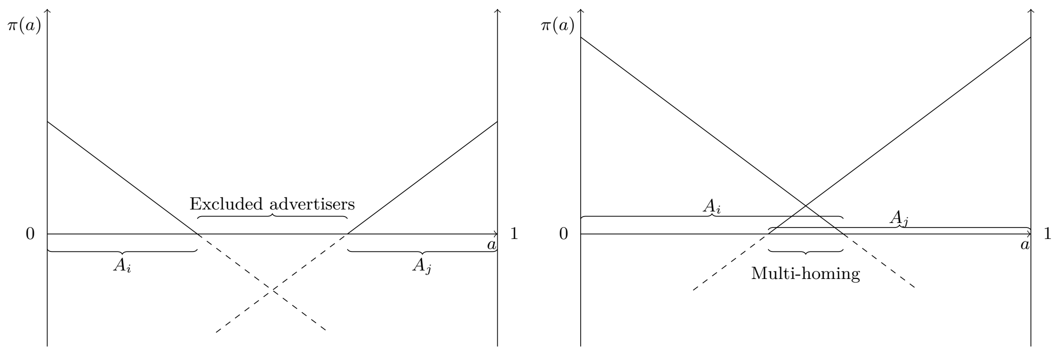

FIGURE 2.2: Relaxed advertiser market assumption

Figure 2.2 shows two potential outcomes of this alternative setup. In the first case the total mass of participating advertisers in the market is smaller than 1 while advertisers 'in the middle' choose not to participate as their transportation costs are too high. In the second case the sets of advertisers joining platform i and j are overlapping such that advertisers 'in the middle' join both platforms, i.e. they multi-home. The remaining analysis follows the steps from the baseline model and is omitted at this point.

The welfare maximizing level of data d_a^o is then given by

$$\kappa'(d_a^o) = A_i^o(d_a^o)\tau'(d_a^o) - A_i^o(d_a^o)\nu'(d_a^o) \tag{2.43}$$

where $A_i^o(d)$ denotes the symmetric mass of advertisers on each platform and is given by $A_i^o(d) = [\tau(d) - \nu(d)]/(2t_a)$. The equilibrium level of data under platform competition d_a^* is then given by

$$\kappa'(d_a^*) = \left(A_i^*(d_a^*)\frac{\nu(d_a^*)}{\tau(d_a^*)} + \frac{t_u}{\tau(d_a^*)} \right) \tau'(d_a^*) - A_i^*(d_a^*)\nu'(d_a^*) \tag{2.44}$$

while $A_i^*(d_a^*) = [(1 - p_a^*(d_a^*))\tau(d_a^*)]/(2t_a)$. We can see immediately that whether the resulting allocation is an equilibrium with multi-homing or with excluded advertisers depends on functional forms and parameters. We will therefore discuss the two cases separately in the following.

Assume transport costs t_a are sufficiently low to allow a multi-homing allocation of advertisers under the efficient benchmark, i.e. $A_i^o(d_a^o) > 1/2$. Comparing the condition for the resulting efficient level of data provision to our baseline condition in (2.12) we see that $d_a^o > d^o$, under multihoming the efficient level of data provision is higher than under single-homing. The idea is that additional advertisers are attracted in order to maximize total value creation in the economy. The comparison of the new competitive level of data provision d_a^* to the new efficiency benchmark as well as to our baseline model is, however, ambiguous. As competition for advertisers is now relaxed, platforms might not be forced to offer high levels of d to attract additional advertisers. At the same the value creation aspect from a larger total number of advertisers is still valid, such that the net effect on the level of data provision remains ambiguous.

When transportation costs t_a are sufficiently large, some advertisers 'in the middle' would not join any platform, such that $A_i^o(d_a^o) < 1/2$ and also $A_i^*(d_a^*) < 1/2$. Note that the efficient level is then also lower than in our benchmark $d_a^o < d^o$ as attracting advertisers becomes relatively expensive and it becomes more efficient to exclude some advertisers than to offer very high levels of d. The comparison to the market outcome, however, remains ambiguous. While the same efficiency argument applies, platforms also have an additional incentive to increase their intensive margin by increasing d

to offset the reduction in advertising demand. Again, depending on functional forms either effect may dominate.

User side

Similarly on the user side, by relaxing Assumption 2.2 it is possible that $\underline{u}$ becomes sufficiently small relative to transportation costs, such that users 'in the middle' prefer to abstain from both platforms. If $\underline{u}$ is sufficiently large relative to transportation costs, users 'in the middle' might choose to join both platforms. In both cases user market shares are determined through the utility of the indifferent user relative to the outside option.

The symmetric welfare-maximizing level of data d_u^o is then given by

$$\kappa'(d_u^o) = X_i^o(d_u^o)\frac{t_u}{\tau(d_u^o) + 2\underline{u} - 2\kappa(d_u^o) - \nu(d_u^o)}\tau'(d_u^o) - \frac{1}{2}\nu'(d_u^o), \tag{2.45}$$

where $X_i^o(d_u^o)$ denotes the symmetric mass of users on each platform and is given by $X_i^o(d_u^o) = [2\underline{u} - 2\kappa(d_u^o) - \nu(d_u^o)]/(2t_u)$. The equilibrium level of data under platform competition d_u^* is then given by

$$\kappa'(d_u^*) = X_i^*(d_u^*)\frac{t_u}{\tau(d_u^*)}\tau'(d_u^*) - \frac{1}{2}\nu'(d_u^*), \tag{2.46}$$

while $X_i^*(d_u^*) = [2\underline{u} - 2\kappa(d_u^*) - \nu(d_u^*)]/(2t_u)$. From this we can immediately see that $d_u^* > d_u^o$, i.e. there is always over-provision of user data. While the efficient benchmark takes into account the tradeoff between excluding users and total value creation, the market outcome only compares the targeting benefit to the exclusion of users. Further note that if the market is not covered such that $X_i(d_u) < 1/2$, the efficient as well as the equilibrium level of data provision is lower than in the baseline model, i.e. $d_u^o < d^o$ and $d_u^* < d^*$ because $t_u/\tau(d) < \delta(d)\ \forall d$.

It is worthwhile to note that under user multi-homing as well as under relaxed user market coverage we get that $\mathrm{d}d_u^*/\mathrm{d}t_u = \mathrm{d}d_u^*/\mathrm{d}t_a = 0$, i.e. the transportation cost parameters on either market side are irrelevant for the equilibrium (and also the efficient) level of data collection. This is because t_u now merely scales demand while the relevant trade-off for the choice of d involves the actual utility from joining the platform, which is unaffected by the demand scale.

Under this setup user demand becomes more elastic than in the baseline model which undermines platforms' incentive to increase d. At the same time platforms would also increase prices $\mathrm{d}p_u^*/\mathrm{d}t_u > 0$ if it becomes increasingly difficult to attract users. Note that we seemingly found the opposite effect in our baseline model $\mathrm{d}p^*/\mathrm{d}t_u < 0$, however, the interpretation of t_u changes substantially such that the two results do not contradict each other: the harder it is to keep users, the higher the prices for advertisers.

In fact platforms are able to overcompensate the reduction in user demand such that $\mathrm{d}\Pi_u^*/\mathrm{d}t_u > 0$ (and for advertisers $\mathrm{d}\pi_u^*/\mathrm{d}t_u < 0$). Again, as the interpretation of t_u essentially reverses, we had the opposite results in our baseline model where platform profits decreased in t_u (while advertiser profits increased). This is also reflected in the effect on the advertiser side where equilibrium prices rise in t_a under both model specifications, i.e. $\mathrm{d}p_u^*/\mathrm{d}t_a > 0$ as the interpretation remains identical.

Positive cross-group externalities

Consider the following modification of the users' utility function:

$$u_i(x) = \underline{u} - \kappa(d_i) + \rho(d_i)A_i - t_u|l_i - x|. \tag{2.47}$$

The concave and twice-differentiable function $\rho(d)$ represents the relevance from a user's point of view of seeing A_i offers, where $\rho'(d) \geq 0$ and $\rho''(d) \leq 0$. However, $\rho(d)$ can now be entirely negative, positive or might even switch signs. The first case is discussed in depth in the main paper, where we consider the case $\rho(d) = -\nu(d)$. The second case, a strictly positive effect, can be thought of as a traditional 'dating' model, where one group strictly enjoys the presence of the other group. The last case can be thought of as a more nuanced version of our nuisance cost in the baseline model. While for low values of d, i.e. the platform has very little information about the consumer, a user dislikes the interaction with the other market side, the interaction might turn out to be valuable once the platform has sufficient information, i.e. d is sufficiently large. A typical example would be the recommendation system on Amazon. While it is debatable, whether Amazon is a two-sided market in the traditional sense, the product recommendation system might serve as a useful example. A new customer might see all kind of product recommendations, some of which are completely useless to the user and are just a waste of attention. However, once Amazon has acquired sufficient information about the user's preferences through analyzing the purchasing and browsing history, the recommendations become more personalized, and the user finds actual value in looking through them.

From a modelling perspective we only require that the relevance is monotonically increasing in the amount of data, but with decreasing returns. Since the curvature of the maximization problem therefore remains unchanged, the characterization of the second order conditions given in the Appendix 2.A.2 also remain qualitatively unchanged. The absolute value of the function $\rho(d)$ is in the end of minor importance regarding the key mechanics of the model, however, it has to be taken care of through appropriately adjusting the modelling assumptions. In order to assure full market coverage on the offer side, we now have the following set of assumptions.

Assumption 2.3 *Competition for advertisers is sufficiently strong, i.e.* $t_a \leq \bar{t}_a$. *For this, it is necessary that competition for users is sufficiently weak and that there* *are gains of trade for all advertisers, even without data collection, i.e.*

$$(a) \quad t_u > |\rho(0)|, \rho(d) < t_u$$
$$(b) \quad t_a < \tau(0)$$

The upper bound on t_a is then given by $\bar{t}_a := \frac{t_u \tau(0) + \rho(0)\tau(0)}{3t_u - \rho(0)}$. Since now net cross-group externalities might be positive, a problem of platform tipping must be taken into account. In particular the following assumption ensures that the competitive symmetric equilibrium leads to positive prices (and therefore positive platform profits), such that a platform would not be indifferent whether to enter the market if just one platform serves the entire market.

Assumption 2.4 *To ensure market participation of both platforms it is necessary to have*

$$t_a t_u > \rho(\cdot)\tau(\cdot).$$

Note that for negative $\rho(\cdot)$ as in our main model, this assumption is always fulfilled as then the RHS is always negative, while the LHS is always positive. Accordingly, if $\rho(\cdot)$ switches signs, the range in which $\rho(\cdot)$ is negative is unproblematic. Therefore the only potentially problematic case is if $\rho(\cdot)$ is positive or can turn positive since it further restricts the parameter space in addition to the previous assumption.[42] Given that both assumptions are satisfied, the analysis is analogous to our main model and all major results still hold.

[42] In the following we sketch a set of conditions under which both assumptions would be satisfied. Note Assumption 2.4 specifies a lower bound $t_a > \underline{t_a}$ with $\underline{t_a} \equiv \frac{1}{t_u}\rho(\cdot)\tau(\cdot)$. It is therefore necessary to show that the set of t_a satisfying Assumptions 2.3 and 2.4 is non-empty. In particular, if it holds that $lim_{d\to\infty}\underline{t_a} < \bar{t_a}$ we can always find intermediate values of t_a satisfying both conditions. For this to be the case it is necessary that $lim_{d\to\infty}\underline{t_a} < \tau(0)$ and that $\rho(\cdot)$ is small if positive.

Chapter 3

Demand Dynamics on Crowdfunding Platforms

Based on Sudaric (2018).

3.1 Introduction

The recent years showed a steep increase in the volume and number of projects financed through crowdfunding (CF). Beginning with the rise of the first online CF platforms in the early 2000s the market for CF has been estimated to reach USD 34 billion in 2015 (Massolution, 2015). Compared to USD 148 billion of venture capital financing (EY, 2016), CF can be seen as a growing but serious addition to the pool of available entrepreneurial financing sources.

In this paper we want to focus on the so called ‘reward-based’ CF following an ‘all-or-nothing’ approach. In this framework consumers pledge towards reaching a funding target. If the amount of total pledges (P) exceeds the target level (T) the campaign is successful. In this case the entrepreneur obtains P, makes the necessary investments, and delivers the reward, usually the product itself, to all project backers. If the target is not reached ($P < T$), the campaign is unsuccessful. In this case no transactions take place (all-or-nothing) and all project backers are refunded.

From the perspective of an entrepreneur this assures that the investment decision is ex-post efficient, which highlights the screening capabilities of a CF mechanism to condition on states of the world where demand is proven to be high enough to make a certain investment worthwhile. Another often attributed advantage of CF is the possibility of market surveying as by observing the outcome of the CF campaign, entrepreneurs can learn about underlining market characteristics and thereby improve future business decisions.

From the consumer perspective there may be concerns whether the project will be successfully funded, and if so, whether the entrepreneur delivers the promised reward and whether the quality is as expected. There might also be concerns whether the entrepreneur moves towards regular sales at different prices after a successful CF campaign.[43] Consumers therefore have to take into account at what conditions they might be able to obtain the product in the future, if they decide not to secure the product through participating in the CF. The last aspect will be the focus of this paper, where we try to better understand demand dynamics in CF campaigns when consumers anticipate future sales.

The following figure depicts the funding outcome of 4.069 CF campaigns in the category ‘video games’ on one of the major CF platforms *Kickstarter* from the period 2009 - 2017.[44] The vertical axis depicts the ratio P/T, i.e. to what extent the project reached its funding threshold such that a ratio $P/T \geq 1$ implies that the project has been successful and potentially over funded, while a ratio $P/T < 1$ means that the funding was unsuccessful as the funding threshold has not been reached.

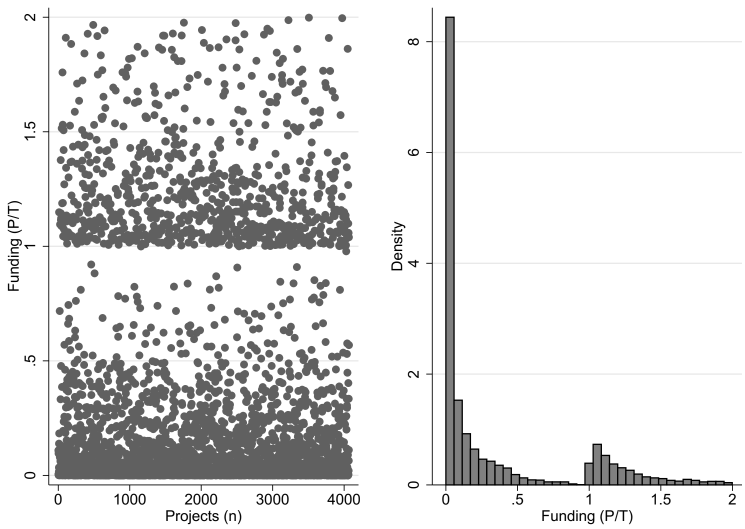

FIGURE 3.1: Distribution of funding outcomes for video games

Of the depicted campaigns roughly 75 percent did not reach the funding target. Interestingly, we see that the majority of those campaigns has a funding ratio of below 0.5 while only few projects ended with funding ratios of $0.5 < P/T < 1$. Similarly, among the 25 percent of successful projects we also observe a skewed distribution, with the majority of successful campaigns having a funding ratio close to one. In the following we want to focus on the second point in more detail.

[43] Mollick and Kuppuswamy (2014) report that 90 percent of successfully funded ventures remained ongoing 1-4 years after the campaign, suggesting that it is reasonable for consumers to consider the possibility of purchasing the product after the CF campaign.

[44] The data has been obtained from the twelve crawling attempts in 2017 available on `https://webrobots.io/kickstarter-datasets/`. We depict finished funding campaigns from the ‘video games’ category with a target level $T \geq 10.000$ USD and pledge level $P > 0$ USD resulting in 4.069 funding campaigns. We restrict the illustration to the ‘video games’ category as it is one of the largest product categories on Kickstarter.

Firstly, consumers might be vary to provide more funding than absolutely necessary in fear of fund embezzlement by the entrepreneur. By limiting demand to the lowest possible level consumers therefore might try to mitigate this *moral hazard risk*. Secondly, consumers might be reluctant to indicate high demand for the project in anticipation of future sales. The entrepreneur might interpret high funding for his project as a signal to change prices in an aftermarket compared to the CF. The restriction of the funding to the minimum can therefore also be seen as a result of consumer coordination to mitigate *price risk*. Thirdly, the clustering could also (at least partly) be due to artificial demand boosts. Suppose an entrepreneur observes a funding of 95 percent one hour before the funding period ends. Obviously, the entrepreneur then has a very strong incentive to contribute own funds (or those of friends and family) in order to reach 100 percent as the alternative would be a transfer of zero due to the all-or-nothing property. Those 'donations' would then lead to a clustering at the target level 'from below'. Lastly, there may be other consumer level reasons which increase the propensity to pledge once the funding goal approaches. Consumers might interpret a higher P/T ratio as a positive quality signal, reassuring them in their pledging decision. They might also feel more pivotal for P/T values approaching one, while the pivotality naturally disappears once the funding goal is reached.

In this project we want to shed light on the first two aspects and in particular on the aspect of price risks. We analyze a two-period setting, where an entrepreneur raises funds to cover setup costs through a reward based all-or-nothing CF campaign (period 1) and sells the good as a monopolist to all remaining consumers in the retail market in case of a successful funding (period 2). The entrepreneur faces uncertainty regarding demand, which is given by a continuum of differentiated consumers in an uncertain market size. We characterize the price risk faced by consumers in anticipation of future prices and show that consumers can be incentivized to participate in the CF campaign by assuring price stability across periods. This is achieved by consumers pledging up to some cutoff valuation, which induces the entrepreneur not to change prices in the subsequent retail market. In particular we present an equilibrium outcome where consumers pledge up to the target level whenever the demand state permits, but never above. The target level in this case serves as a commitment device to leave prices unchanged, eliminating the price concerns for consumers. This is consistent with the price risk argument introduced above and provides a novel explanation for the empirical observation of the clustering around the target level. We also present a variety of robustness checks and show that the clustering at the target level prevails if we change the source of uncertainty, the timing of consumer arrivals, as well robustness with respect to moral hazard.

3.2 Related literature

This paper contributes to the growing literature on crowdfunding. Agrawal et al. (2014) discuss the economic mechanisms at work associated with a CF scheme but do not provide formal analysis. Similarly, Belleflamme et al. (2015) provide a very helpful overview of the economics behind crowdfunding with a slight focus on the platform aspect of crowdfunding providers.

One stream of the theoretical contributions focuses on the possibility to use CF to price discriminate between consumers. Belleflamme et al. (2014) analyze the trade-offs between reward-based and equity-based crowdfunding and analyze how crowdfunding can be used to price discriminate between crowdfunders and non-crowdfunders. In their model consumers obtain additional utility from playing an active role in the funding period which we do not take into account. Even though this effect certainly plays a role in some funding projects (niche markets, 'emotional' products, etc.), we expect the effect to dissipate once the number of potential funders becomes large. Ellman and Hurkens (2015) study the optimal CF design and find that CF can be used to extract rents from high-valuation consumers when they are pivotal for the success of a campaign. A similar argument is made in Kumar et al. (2016) where a pivotality argument is used to force some consumers to pay a premium compared to a future retail price. Our model differs from the two mentioned papers as we consider continuous demand and therefore no individual consumer is pivotal for the success of the campaign, as we expect pivotality to play a less crucial role once the CF industry matures and becomes more accepted and popular. Also, Ellman and Hurkens (2015) consider the presence of an aftermarket in an extension to their main model but restrict the distribution of consumers, such that some consumers are only available throughout the CF campaign, while other consumers are only available in the aftermarket. This is in contrast to our paper, as we allow all consumers to endogenously decide whether to participate in the CF or whether to wait for the retail stage.

Another stream of literature analyzes the role of CF to overcome demand uncertainty and to learn about underlining demand characteristics. In fact the survey by Mollick and Kuppuswamy (2014) suggests that in more than 60 percent of CF campaigns one consideration was to see whether there is demand for the product. Similarly, the analysis by Viotto da Cruz (2018) suggests that CF is used to learn about potential demand. Chemla and Tinn (2018) show that CF can improve investment decisions as they provide information about the demand prior to making the investment. The gathered information can then be used in subsequent sales decisions. However, in their setting the distribution of consumers across periods is exogenously constrained. In fact, they assume that only a fixed number of consumers has access to the crowdfunding campaign. Strausz (2017) analyzes the problem from a mechanism design perspective and argues that CF can help to screen for valuable projects as it only allows for project implementation in case of sufficiently high demand. Additionally, the author argues that crowdfunding can help to overcome a moral hazard problem by providing the entrepreneur only the necessary funds to cover investment costs, while deferring remaining funds to a point in time after the investment is sunk, discouraging fund embezzlement. The author argues that these deferred payments arise naturally in a setting where the CF campaign is followed by sales in a retail market, but does not model the aftermarket explicitly. Our results suggest that consumers distribute endogenously across the CF and the retail period and that the distribution of consumers can indeed incentivize an entrepreneur to implement the investment project as long as the moral hazard risk is not too severe. Chang (2016) also considers a two-period setup with a continuum of potential backers, however the setting differs substantially as the author considers uncertainty regarding the common value of the crowdfunded object.

Several papers focus on demand dynamics explicitly and try to provide explanations for empirical findings. Alaei et al. (2016) analyze the pledging behavior in a setting where consumers arrive sequentially to the market. They show that the success probability of a CF campaign is bimodal such that campaigns are either very likely to fail or very likely to succeed. On a similar note, unpublished work by Deb et al. (2018) studies contribution dynamics where donations are taken into account. The authors show that in the presence of donors the target level becomes flexible to some extent, as any shortcoming towards the end of the campaign can be covered by an endowed donor to make sure that the campaign succeeds. On the empirical side, analysis by Mollick (2014) suggests that CF projects tend to either succeed by a small margin or fail by a large margin, which is consistent with the illustration in figure 3.1. Kuppuswamy and Bayus (2017) argue that consumers are more likely to pledge if they believe that their contribution will make an impact. The pledging propensity therefore increases when the funding approaches the target level, and decreases once the target is reached.[45] We contribute to this stream of literature by providing a novel explanation for the clustering around the target level, namely the mitigation of price risk.

We would like to relate our work also to the broader literature on advance purchasing and price setting of durable goods monopolists. The Coase conjecture (Coase, 1972) states that a durable good monopolist can not engage in intertemporal price discrimination if consumers are forward looking. This aspect reappears in our analysis, as in fact consumers in equilibrium are indifferent between pledging in the CF campaign and waiting for the retail market. The difference, however, is that the price setting in the retail period is adapted to information obtained throughout the CF campaign, while at the same time the all-or-nothing property demands a lower bound on revenue obtained in the CF campaign. Nocke and Peitz (2007) show

[45] We refer to Kuppuswamy and Bayus (2017) for an overview of the literature in psychology and experimental economics which supports the 'goal gradient' tendency.

that in a two-period setting consumers with high valuation buy early at a higher price while low valuation consumers wait for the price to drop (clearance sales). However, the setting differs substantially as production is capacity constrained in their model and consumers have a discrete type space (high and low). Nevertheless our results correspond nicely to theirs, as in our setting high-value consumers buy early in order to balance the learning effect a successful crowdfunding campaign would have. Similarly, Möller and Watanabe (2010) show that if demand exceeds capacity, clearance sales as well as advance purchase discounts can be optimal. Sahm (2015) extends the advance purchase framework to a setting with continuous type space but a discrete number of consumers. He shows that advance purchase pricing can be used as a discriminatory device, however, the price difference between the two periods disappears as the number of consumers becomes large, which is consistent with our results.

3.3 Model

We consider a model with three groups of players (consumers, entrepreneur and CF platform) being respectively involved in the financing, production and sales of an innovative good. The game is separated into two periods. Period 1 refers to the CF period which spans $t \in [0, 1]$ while period 2 refers to the retail market, where sales to the general public occur in case of a successful CF campaign, i.e. after $t > 1$.

3.3.1 Players

Consumers There is a continuum of consumers with total mass $M(s)$. The total mass $M(s)$ depends on an exogenous but stochastic demand state $s \in S \equiv [0, 1]$ where we assume $M(s) = s \; \forall \; s \in S$, reflecting uncertainty regarding the total market size. We denote the distribution of s as $F(s)$ with $F'(s) = f(s) > 0 \; \forall s \in S$ and assume for tractability reasons that demand states are uniformly distributed such that $F(s) = s$. Each consumer wants to buy one unit of the good and has a private valuation $v \in V \equiv [0, 1]$ where v is distributed according to $G(v)$ with $G'(v) = g(v) > 0 \; \forall \; v \in V$ such that in every state s there is a full support of valuations v in the market.[46] Further we require the distribution of valuations to satisfy the following property.

Assumption 3.1 (Monotone hazard rate) *The distribution of valuations $G(v)$ is twice continuously differentiable and exhibits a monotone hazard rate $H'(v) < 0$ where $H(v) := \frac{1-G(v)}{g(v)}$ for all $v \in V$.*

Let the one-shot revenue maximizing price be denoted as p^M which is implicitly defined by $p^M = H(p^M)$. Consumers are risk-neutral and have no time preference (i.e. a discount rate of one) and obtain zero utility if they decide not to purchase the

[46]We consider an alternative uncertainty setup where the distribution of valuations depends on the demand state in section 3.5.4.

good. A consumer with valuation v then simply obtains a (net) utility of $u = v - p$ when purchasing the good at price p.

Entrepreneur There is one entrepreneur (E) with an innovative product idea. In order to set up production of the good E faces publicly known investment costs of $I > 0$. Once the initial investment is sunk, E can produce the good at marginal costs of zero. We assume that E is money-less and relies on external financing in order to cover investment cost. Also, suppose the good is sufficiently innovative such that E is a monopolist once production is set up. We assume that E can not commit to period 2 prices during the CF stage. Also in the main model we ignore the possibility of moral hazard, i.e. whenever E obtains the necessary funds to cover investment costs she will do so.[47]

Crowdfunding platform We consider an entirely passive CF platform which facilitates a reward-based, all-or-nothing CF mechanism $\psi = (p_1, T)$, which is chosen by E. The mechanism resembles popular CF services such as *Kickstarter* in a sense that it requires every CF project to specify an individual pledge level $p_1 \geq 0$ and a target level $T \geq I$. We assume that the campaign length is fixed for a period of length 1 and starts with the choice of ψ at $t = 0$.

If the sum of total pledges P exceeds the target level T the CF is successful, and the pledge level P is transferred to the entrepreneur. The obligation of E in this case is to make the necessary investment, to produce the good and to deliver the good to all backers free of any additional charges. The initial individual pledge level p_1 can therefore be thought of as an advance purchase price, while the promised reward of the CF campaign is one unit of the product itself. If the target level has not been reached ($P < T$) the CF is unsuccessful. Consumers in this case get their individual pledge p_1 back and E does not get any funds transferred (all-or-nothing, AoN). We assume for simplicity that the CF platform provides its service free of charge.

3.3.2 Information structure and timing

We assume that consumers know their private value v while the distribution of valuations, the distribution of demand states as well as the game structure are common knowledge among all players. The realization of the demand state $s \in S$ is unobservable by all players and we assume that players update their beliefs in a Bayesian sense whenever possible. The time structure of the game is depicted in the following figure.

[47] In section 3.5.3 we discuss how introducing moral hazard affects the results. In particular we consider the setting where instead of making the investment, E can decide to embezzle the transferred funds.

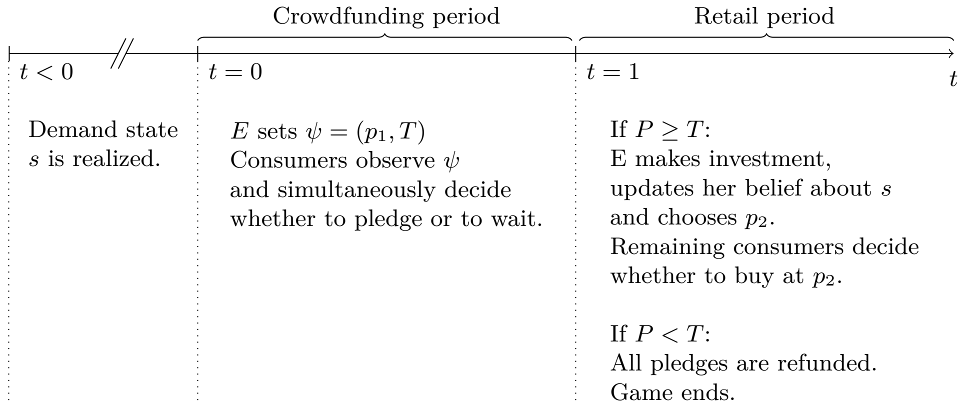

FIGURE 3.2: Timing

3.4 Equilibrium analysis

In this section we introduce notation and derive equilibrium conditions from the consumers' and the entrepreneur's decision problems. We then characterize two equilibrium outcomes, an uncoordinated equilibrium and a coordinated equilibrium. In cases where we make use of the expectation operator, we take the expectation with respect to the demand state. Parts of the analysis (Appendix 3.A.1) and proofs (Appendix 3.A.2) are delegated to the appendix whenever they are not central to the understanding of the paper.

3.4.1 Decision problems

Let $\psi = (p_1, T)$ denote an arbitrary CF campaign. Reflecting the aggregate uncertainty in the market we characterize demand using consumer specific pledging probabilities such that $b(p_1|v, s)$ denotes the probability to pledge at price p_1 of a consumer with valuation v in demand state s. Further note that consumers do not learn anything about the underlining demand state by just learning their valuation v such that consumers and the entrepreneur share the common prior $f(s)$.[48]

Consumers Consider the decision problem of a consumer with valuation v whether to pledge or not for a given CF scheme $\psi = (p_1, T)$. We start by deriving demand states where the CF campaign is expected to be successful. For a given CF scheme ψ we can denote state dependent demand in period 1 as

$$D_1(p_1|s) = s \int_{p_1}^{1} b(p_1|s, v) g(v) dv. \tag{3.1}$$

The demand specification $D_1(p_1|s)$ simply takes into account the pledging decisions of consumers with sufficiently high valuation such that the total pledge level in state

[48]Note $f(s|v) = f(s)g(v) / \left(\int_{s \in S} f(s)g(v)ds \right) = f(s) \; \forall \; v \in V$.

s is given by

$$P(p_1|s) = p_1 D_1(p_1|s). \tag{3.2}$$

We can then define the set of demand states where the CF campaign is expected to be successful as $\underline{S} := \{s \in S | P(p_1|s) \geq T\}$ and let $\underline{f}(s) := f(s|s \in \underline{S}) \equiv f(s)/\left(\int_{s\in\underline{S}} f(s)ds\right)$ denote the distribution of states conditional on the CF campaign being successful. As individual consumers have zero mass, no consumer can be made pivotal for the success of the CF campaign. The decision whether to pledge or not is then given by the comparison of expected utilities. A consumer with $v \geq p_1$ will therefore strictly prefer participation in the CF campaign if $\mathbb{E}[u('pledge')] > \mathbb{E}[u('wait')]$ or explicitly

$$\pi_s(v - p_1) + (1 - \pi_s)0 > \pi_s \left(\int_{s\in\underline{S}} \max\{v - p_2(p_1|s), 0\} \underline{f}(s)ds \right) + (1 - \pi_s)0 \tag{3.3}$$

where $\pi_s := \Pr(s \in \underline{S}) \equiv \int_{s\in\underline{S}} f(s)ds$ denotes the success probability, while $p_2(p_1|s) := p_2^*(p_1, P(p_1|s))$ denotes the anticipated retail price in case a pledge level $P(p_1|s)$ is reached. The retail price setting will be introduced below in more detail. Note that the comparison of expected utilities takes into account that in case of an unsuccessful campaign, consumers are refunded if they pledged, while the retail stage also only becomes relevant if the CF campaign succeeds. The considerations in the retail stage then reflect the idea that no consumer can be forced to purchase the product if the price exceeds the consumer's valuation, as the consumer always has the outside option to not buy the product at all. The comparison $\mathbb{E}[u('pledge')] \gtreqless \mathbb{E}[u('wait')]$ for consumers $v \geq p_1$ reduces to

$$v - p_1 \gtreqless \int_{s\in\underline{S}} \max\{v - p_2(p_1|s), 0\} \underline{f}(s)ds \tag{3.4}$$

which highlights the price risk faced by consumers with valuation $v \geq p_1$, while consumers with $v < p_1$ will always wait, as they can only profit from waiting. For consumers with valuations close to p_1 the LHS of (3.4) is essentially zero, such that consumers might benefit from waiting in case there are demand states where prices would decrease. If prices increase they might not purchase the good at all, and obtain a utility of zero. Consumers with high valuations compare a high net utility from pledging at p_1 to an uncertain surplus of waiting. In particular if prices increase above p_1, high valuation consumers might end up worse compared to pledging in the CF campaign. For $\underline{S} \neq \emptyset$ we therefore obtain the optimal pledging decision

$$b^*(p_1|v) = \begin{cases} 1 & \text{if } \mathbb{E}[u('pledge')] > \mathbb{E}[u('wait')] \text{ and } v \geq p_1 \\ \beta \in [0,1] & \text{if } \mathbb{E}[u('pledge')] = \mathbb{E}[u('wait')] \text{ and } v \geq p_1 \\ 0 & \text{if } \mathbb{E}[u('pledge')] < \mathbb{E}[u('wait')] \text{ or } v < p_1. \end{cases} \tag{3.5}$$

Consumers will therefore pledge if their valuation is sufficiently high and the expected utility from securing the good in the retail stage is sufficiently low. They will wait if their valuation is too low compared to current prices, or the expected utility from waiting is sufficiently high. In case they are indifferent between pledging and waiting, any pledging probability is individually rational.

Entrepreneur Starting in period 2 we can characterize the optimal pricing decision in the retail market. Suppose the campaign has been successful such that E observes some pledge level $P \geq T$. This gives rise to an updated set of demand states $\hat{S} := \{s \in S | P(p_1|s) = P\}$ which are consistent with observing P, and a conditional distribution $\hat{f}(s) := f(s|s \in \hat{S}) \equiv f(s)/\left(\int_{s\in\hat{S}} f(s)ds\right)$. Also for all $s \in \hat{S}$ we can define residual demand in period 2 as

$$D_2(p_2|s, p_1) = s \int_{p_2}^{1} (1 - b(p_1|s, v))\, g(v)dv \tag{3.6}$$

such that the retail profits are given by $\Pi_2(p_2|s, p_1) = p_2 D_2(p_2|s, p_1)$ for $s \in \hat{S}$ while the profit maximization problem is given by $\max_{p_2} \mathbb{E}[\Pi_2(p_2|s, p_1)|P] = \int_{s\in\hat{S}} \Pi_2(p_2|s, p_1)\hat{f}(s)ds$. The optimal retail price is then given by

$$p_2^*(p_1, P) = \arg\max_{p_2} \mathbb{E}[\Pi_2(p_2|s, p_1)|P] \tag{3.7}$$

which we assume to be unique at this point and verify in the subsequent analysis that this is the case. Further, we define $\Pi_2^*(p_1, P) := \mathbb{E}[\Pi_2(p_2^*(p_1, P)|s, p_1)|P]$. We can now write ex-ante period 1 profits as

$$\Pi_1(p_1|s) = \begin{cases} P(p_1|s) - I & \text{if } s \in \underline{S} \\ 0 & \text{else} \end{cases} \tag{3.8}$$

such that period 1 profits are given by the difference between the total money collected in the CF campaign $P(p_1|s)$ and the investment costs I in case of a successful campaign ($s \in \underline{S}$). If the campaign is not successful ($s \notin \underline{S}$) the AoN property of the CF mechanism yields zero profits. Similarly, ex-ante retail profits are given by

$$\Pi_2(p_1|s) = \begin{cases} \Pi_2^*(p_1, P(p_1|s)) & \text{if } s \in \underline{S} \\ 0 & \text{else} \end{cases} \tag{3.9}$$

as the retail stage is only relevant in case of a successful CF campaign. Lastly, we require the CF scheme to be ex-ante optimal such that

$$\psi^* = \arg\max_{\psi} \mathbb{E}\left[\Pi_1(p_1|s) + \Pi_2(p_1|s)\right] \text{ s.t. } T \geq I \tag{3.10}$$

where $T \geq I$ simply denotes the feasibility constraint.

Equilibrium considerations Equations (3.5), (3.7) and (3.10) are optimality conditions which have to be satisfied in equilibrium. They require sequential rationality by the entrepreneur whenever period 2 is reached, as well as ex-ante optimal behavior by the entrepreneur and consumers given the common prior belief.

Inequality (3.4) illustrates the price risk faced by consumers which is the key obstacle to overcome for defining equilibrium demand. We therefore introduce the following preliminary considerations to motivate the construction of our presented equilibrium outcomes.

Proposition 3.1 *There can not exist an equilibrium in which a CF campaign $\psi = (p_1, T)$ implements an investment project $I > 0$ in states $s \in \underline{S}$ if consumers with $v \geq p_1$ strictly prefer waiting over pledging, or if consumers with $v \geq p_1$ strictly prefer pledging over waiting.*

Proof. The following constitutes a proof by contradiction. Suppose there is an equilibrium where consumers are not indifferent. If all consumers $v \geq p_1$ prefer waiting, total demand in period 1 is zero, such that a project with investment cost $I > 0$ can not be implemented. A contradiction. Now suppose that all consumers with $v \geq p_1$ prefer to pledge. This implies that there is no consumer left with valuation $v \geq p_1$ in period 2, such that the profit maximizing retail price must be below p_1. Hence, consumers would be better off by waiting instead of pledging, a contradiction. □

To gain intuition for this result ignore the demand uncertainty and suppose I is very small. Now consider the two extreme cases where for a given p_1 demand is either very low or very high. If demand is high most consumers with $v \geq p_1$ are not available in the retail period anymore as they purchased the product in the CF period, resulting in retail prices below p_1. If demand is very low, on the other hand, E faces essentially the one-shot monopoly problem in period 2. This gives rise to a further intermediary thought.

Lemma 3.1 *There can not exist an equilibrium in which a CF campaign $\psi = (p_1, T)$ implements an investment project $I > 0$ in states $s \in \underline{S}$ if $p_1 \geq p^M$.*

Proof. See Appendix. □

Given Lemma 3.1 we continue our analysis with the implicit assumption $p_1 < p^M$ and continue with our equilibrium considerations. Proposition 3.1 remains silent about the case where consumers with $v \geq p_1$ are indifferent between pledging and waiting. One straight forward way to achieve this, is to establish price stability across periods, i.e. once a CF price p_1 is chosen, the retail price must not change in case of a successful campaign. This completely eliminates the price risk faced by consumers and therefore in particular renders consumers with $v \geq p_1$ indifferent. As we assume no price commitment by the entrepreneur regarding retail prices prior to period 2, this has to be achieved by adequate distribution of demand across the two periods. This is the key idea behind our proposed equilibrium outcomes and is summarized in the following Proposition.

Proposition 3.2 (Stability condition) *There exist price-stable equilibria in which a CF campaign $\psi = (p_1, T)$ implements an investment project $I > 0$ in states $s \in \underline{S}$, where prices remain unchanged in case of successful CF campaign such that*

$$p_2(p_1|s) = p_1 \ \forall \ s \in \underline{S}, \tag{3.11}$$

rendering all consumers with $v \geq p_1$ indifferent between pledging and waiting.

The existence of such equilibria is demonstrated in the following sections. We will refer to Proposition 3.2 as 'stability condition' throughout the subsequent analysis, as the condition will play a crucial role in defining demand in more detail and in the construction of the presented equilibrium outcomes. In the following we present two equilibrium outcomes: an uncoordinated and a coordinated equilibrium, both satisfying the stability condition and allowing for implementation of the investment project.

3.4.2 Uncoordinated equilibrium

In absence of any coordination device consumer decisions can not coordinate on a specific demand level in the CF period. Suppose that pledging decisions are characterized by a cutoff valuation $\overline{v}(p_1)$ such that

$$b(p_1|v, s) = \begin{cases} 1 & \text{if } v \geq \overline{v}(p_1) \geq p_1 \\ 0 & \text{else} \end{cases} \tag{3.12}$$

for all states $s \in S$ such that for a given p_1 only consumers with valuation $v \geq \overline{v}(p_1)$ pledge, while consumers with $p_1 \leq v < \overline{v}(p_1)$ refrain from pledging, resulting in period 1 demand of $D_1(p_1|s) = s(1 - G(\overline{v}(p_1))$.[49] Now suppose $P \geq T$. Observing P is then perfectly informative about the underlining demand state as then $P = sp_1(1 - G(\overline{v}(p_1))$ such that $\hat{S}$ is a singleton containing only the true demand state s. Residual demand in period 2 is then given by

$$D_2(p_2|s, p_1) = \max\left\{s\left(G(\overline{v}(p_1)) - G(p_2)\right), 0\right\}, \tag{3.13}$$

[49] Note that this resembles a rationing rule as not all consumers with $v \geq p_1$ are served in period 1 but only consumers with high valuations $v \geq \overline{v}(p_1)$. This 'efficient' rationing is discussed at a later stage in more detail. In section 3.5.5 we demonstrate that in fact there can not exist a price-stable equilibrium where the alternative rationing rule of 'proportional rationing' is applied such that all consumers $v \geq p_1$ mix with a probability $\beta \in (0, 1)$.

resulting in the profit maximization problem

$$\max_{p_2} \mathbb{E}\left[\Pi_2(p_2|s,p_1)|P\right] = \max_{p_2} p_2 D_2(p_2|s,p_1). \tag{3.14}$$

The profit maximizing retail price $p_2^*(p_1, P)$ is implicitly defined by

$$p_2^* = \frac{G(\overline{v}(p_1)) - G(p_2^*)}{g(p_2^*)}. \tag{3.15}$$

Note that the optimal retail price does not depend on the demand state s or the total pledge level P such that we can denote the optimal retail price simply as $p_2^*(p_1)$. The stability condition for consumers in Proposition 3.2 is therefore only satisfied if $p_2^*(p_1) = p_1$. It is easy to verify that this is the case for

$$\overline{v}(p_1) = G^{-1}\left(G(p_1) + p_1 g(p_1)\right) \tag{3.16}$$

as (3.15) then reduces to $G(p_2^*) + p_2^* g(p_2^*) = G(p_1) + p_1 g(p_1)$ which is only satisfied for $p_2^* = p_1$.[50] Further, $\overline{v}(p_1)$ is well defined for all $p_1 \in [0, p^M]$ such that $\overline{v} : [0, p^M] \mapsto [0, 1]$ while we would have $p_2^*(p_1) > p_1$ for cutoff valuations above $\overline{v}(p_1)$ and $p_2^*(p_1) < p_1$ for cutoff valuations below $\overline{v}(p_1)$.[51] Also, we have $\overline{v}'(p_1) > 0$ for $p_1 \in [0, p^M]$ with $\overline{v}(0) = 0$ and $\overline{v}(p^M) = 1$.

To gain intuition for $\overline{v}(p_1)$ first ignore the term $p_1 g(p_1)$ such that $\overline{v}(p_1) = G^{-1}(G(p_1)) = p_1$. Then all consumers with $v \geq p_1$ would pledge, resulting in a profit maximizing retail price strictly below p_1. Hence, to push p_2^* towards p_1, we need to make consumers with valuations $v > p_1$ available in the retail period, which is done by increasing the cutoff valuation above p_1. By adding the term $p_1 g(p_1)$ the cutoff valuation is increased precisely to the extent that the monopoly price facing the residual demand p_2^* is equal to p_1.

Turning to the consumer decisions and recalling $P(p_1|s) = p_1 D(p_1|s)$ we obtain the set of success states $\underline{S} = \{s \in S | P(p_1|s) \geq T\} \equiv [\underline{s}, 1]$ as $P(p_1|s)$ is increasing in s, while the lowest success state $\underline{s}$ is defined by the state where the target level is barely reached $P(p_1|\underline{s}) = T$ such that

$$\underline{s} = \min\left\{\frac{T}{p_1\left(1 - G(\overline{v}(p_1))\right)}, 1\right\}. \tag{3.17}$$

We immediately see that the stability condition is satisfied as then $p_2(p_1|s) = p_2^*(p_1) = p_1 \ \forall \ s \in \underline{S}$ such that in particular $b^*(p_1|v) = b(p_1|v,s)$ is optimal. Total expected

[50] This is a direct implication of the monotonicity result established in Lemma 3.4 in Appendix 3.A.1.

[51] To see this note that trivially $G(p_1) + p_1 g(p_1) \geq 0$ while $G(p_1) + p_1 g(p_1) \leq 1$ can be rearranged to $p_1 \leq H(p_1)$ which is satisfied for all $p_1 \leq p^M$. For the inequalities note that for $\overline{v} \to 1$ we have $p_2^* \to p^M$, while for $\overline{v} \to 0$ we have $p_2^* \to 0$.

profit is then given by

$$
\begin{aligned}
\mathbb{E}\left[\Pi_1(p_1|s) + \Pi_2(p_1|s)\right] &= \int_0^1 \left[\Pi_1(p_1|s) + \Pi_2(p_1|s)\right] f(s)ds \\
&= \int_{\underline{s}}^1 \left[\Pi_1(p_1|s) + \Pi_2(p_1|s)\right] f(s)ds \\
&= \int_{\underline{s}}^1 \left[sp_1(1 - G(p_1)) - I\right] ds \\
&= \frac{1}{2}(1 - \underline{s}^2)p_1(1 - G(p_1)) - (1 - \underline{s})I \\
&= (1 - \underline{s}) \left[\frac{1}{2}(1 + \underline{s})p_1(1 - G(p_1)) - I\right] \\
&= \underbrace{(1 - F(\underline{s}))}_{\text{Success probability}} \underbrace{\left[\mathbb{E}[s|s \geq \underline{s}]p_1(1 - G(p_1)) - I\right]}_{\text{Expected profit in case of success}} \qquad (3.18)
\end{aligned}
$$

such that the ex-ante profit maximization program can be written as

$$\max_{\psi=(p_1,T)} (1 - F(\underline{s})) \left[\mathbb{E}[s|s \geq \underline{s}]p_1(1 - G(p_1)) - I\right] \text{ s.t. } T \geq I. \qquad (3.19)$$

We can immediately see that the feasibility constraint $T \geq I$ is binding as rearranging $\partial\mathbb{E}\left[\Pi_1(p_1|s) + \Pi_2(p_1|s)\right]/\partial T < 0$ yields

$$\frac{I}{T} < \frac{1 - G(p_1)}{1 - G(\overline{v}(p_1))} \qquad (3.20)$$

which is satisfied as we have $LHS \leq 1$ due to the feasibility constraint, while $RHS > 1$ for all $p_1 \in (0, p^M)$. Also, we indeed obtain $p_1^* \in (0, p^M)$ as the success probability approaches zero for $p_1 \to p^M$.

3.4.3 Coordinated equilibrium

Going back to figure 3.1, we see that the uncoordinated outcome presented in section 3.4.2 fails to explain the clustering around $P/T = 1$. We would therefore like to analyze in the following whether we can explain this pattern by equilibrium pledging behavior if consumers are able to coordinate on a certain pledge level. In particular, suppose that demand is such that the target level T is reached whenever possible and demand is rationed (efficiently) if potential demand in a given state would exceed the target level. We discuss how this type of coordination might occur at a later point in this section. Demand is then characterized by state dependent cutoff valuations $\overline{v}(p_1|s)$ which are given for a chosen target level T by

$$\overline{v}(p_1|s) = \begin{cases} G^{-1}\left(1 - \frac{T}{sp_1}\right) & \text{if } s \geq \underline{s} \\ p_1 & \text{else} \end{cases} \qquad (3.21)$$

while $\underline{s} = \min\left\{T/\left(p_1(1 - G(p_1))\right), 1\right\}$. The idea behind this pledging pattern is that consumers pledge until the target level is reached, irrespective of the demand state. If potential demand would exceed the target level T, demand is rationed 'efficiently' in the sense that only consumers with high valuations pledge in order to reach the target level.[52] Note that if the stability condition holds, the applied rationing rule does not 'harm' consumers, as all consumers with $v \geq p_1$ are indifferent, and are eventually served at p_1 in case of a successful campaign. The suggested rationing then merely allocates demand across periods. From a technical point of view the main difference to the setup in section 3.4.2 is that the cutoff valuation is now state-dependent. Note that $\partial\overline{v}(p_1|s)/\partial s > 0$ while $\overline{v}(p_1|s) \geq p_1$ and $\overline{v}(p_1|\underline{s}) = p_1$ by construction.

Suppose the CF campaign has been successful, i.e. the total pledge level $P = T$ has been reached. From observing the total amount T the entrepreneur can no longer perfectly infer which valuations have left the market. In particular, observing T is then consistent with state dependent period 1 demand

$$D_1(p_1|s) = s\,(1 - G(\overline{v}(p_1|s))) \tag{3.22}$$

for all states s in $\hat{S} = \{s \in S|P(p_1|s) = T\} \equiv [\underline{s}, 1] = \underline{S}$. In state $\underline{s}$ all consumers with valuation $v \geq p_1$ must have pledged in order to reach T. In states $s > \underline{s}$ the total pledge level T was a result of 'rationing' behavior such that only consumers with valuations $v \geq \overline{v}(p_1|s)$ have pledged while consumers with valuation $p_1 \leq v < \overline{v}(p_1|s)$ refrained from pledging. Residual demand is then given by

$$D_2(p_2|s, p_1) = \max\left\{s\left(G(\overline{v}(p_1|s)) - G(p_2)\right), 0\right\}. \tag{3.23}$$

such that the maximization problem in period 2 after observing a total pledge level T can be written as

$$\max_{p_2} \mathbb{E}\left[\Pi_2(p_2|s, p_1)|T\right] = \int_{\underline{s}}^{1} p_2 D_2(p_2|s)\underline{f}(s)ds. \tag{3.24}$$

The profit maximizing retail price $p_2^*(p_1, T)$ then exhibits the following characteristics.

Lemma 3.2 *The profit maximizing retail price $p_2^*(p_1, T)$ satisfies*

$$p_2^*(p_1, T) > p_1 \text{ for } T < T^*, \tag{3.25}$$

$$p_2^*(p_1, T) < p_1 \text{ for } T > T^*, \tag{3.26}$$

$$p_2^*(p_1, T) = p_1 \text{ for } T = T^* \tag{3.27}$$

where

$$T^* = p_1(1 - G(p_1))\frac{1 - G(p_1) - p_1 g(p_1)}{1 - G(p_1) + p_1 g(p_1)}. \tag{3.28}$$

[52] In section 3.5.5 we demonstrate that there can not exist a price-stable equilibrium with the alternative of a 'proportional' rationing rule.

Proof. See Appendix. □

Lemma 3.2 demonstrates how the total pledge level translates into informational updating regarding the optimal price setting in the retail period. If E would observe $P = T < T^*$ she would believe that there are still enough consumers with sufficiently high valuation in the market such that prices can be profitably increased to $p_2^* > p_1$. Similarly, observing $P = T > T^*$ would induce E to believe that too many consumers with high valuations pledged during the CF campaign, such that the profit maximizing strategy is now to offer the product at lower prices in the retail stage ($p_2^* < p_1$). If, however, E observes a total pledge level of $P = T = T^*$, the profit maximizing strategy is precisely not to change prices, i.e. the expected residual demand is such that some consumers with very high valuations left the market, but the mass of consumers with $v \geq p_1$ is still sufficiently high such that it is optimal to not reduce prices in the retail stage. Figure 3.3 depicts the profit maximization problem for different total pledge levels. We see that the pledge level essentially scales the expected

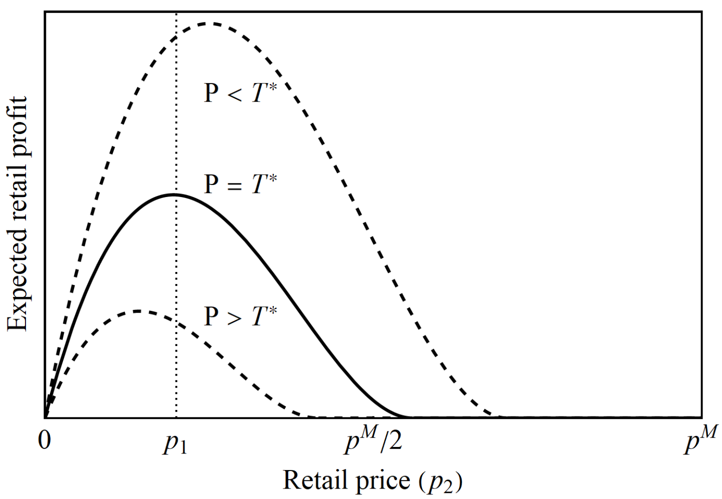

FIGURE 3.3: Period 2 profit maximization problem

The figure illustrates the period 2 profit maximization problem for the specification $G(v) = v$, $p_1 = 0.1$ and varying levels of T. Investment costs I are assumed to be sufficiently low such that the CF campaign is successful in all depicted scenarios.

period 2 profit and thereby shifts the profit maximizing price outwards. For $T = T^*$ the expected period 2 profit is scaled in a way that the profit maximizing price exactly coincides with p_1.

We can interpret Lemma 3.2 also from a consumer perspective. As long as the total pledge level is below T^*, the profit maximizing retail price is above p_1, which means that consumers have a strong incentive to pledge during the CF campaign as long as T^* has not been reached yet. Once T^* has been reached, consumers have no incentive to continue pledging, as increasing the total pledge level above T^* would result in low retail prices, i.e. the 'last' pledgers would have been better off by waiting instead of pledging. If the total pledge level is exactly T^* no consumer has an incentive to deviate, as prices in both periods are the same. It is clear that for a given p_1 a target level $T = T^*$ satisfies the stability condition as then $p_2^*(p_1, T^*) = p_1 \ \forall \ s \in \underline{S}$.

The problem is that even though all consumers with $v \geq p_1$ are indifferent, the existence of this equilibrium depends on state dependent consumer strategies. Since the demand state is unknown to consumers, we argue in the following how this type of coordination might occur. The coordination requires that 1) the target is reached whenever possible and 2) in case potential demand would exceed T^* the rationing rule is applied, such that only consumers with the highest valuations pledge. If such a coordination possibility exists, then the individual pledging decision $b^*(p_1|v)$ is consistent with aggregate pledging probabilities $b(p_1|v, s)$ as individual consumers are indifferent such that any probability $\beta \in [0, 1]$ is optimal. The coordination then allocates 'appropriate' probability values (either 0 or 1) in order to reach the target level.

The first point is consistent with the concept of 'payoff dominance' (Harsanyi and Selten, 1988) as it guarantees implementation of the project whenever possible and excludes the possibility of project failing due to indifferent consumers.[53]. Another justification for this point would be that being part of the group of backers has some intrinsic value to consumers, breaking the indifference in favor of pledging (see e.g. Belleflamme et al. 2014). Lastly, the target level acts as a focal point easing coordination.

The second point reflects the efficient rationing assumption from the literature on pricing and competition under capacity constraints (see e.g. Kreps and Scheinkman, 1983) where even though multiple consumers would be able to buy a product, the good is allocated to the consumer with the highest valuation. One interpretation in the CF setting would be that consumers with high valuation are more likely to pledge, as they become aware of the CF campaign earlier than consumers with low valuations. Once a sufficient amount of high valuation consumers have pledged, low valuation consumers no longer find it optimal to do so. This idea already hints at a notion of sequentiality. In section 3.5.2 we take the sequentiality argument more serious and demonstrate that the outcome is equivalent to a situation where consumers indeed arrive sequentially.[54]

We demonstrated that picking $T = T^*$ induces indifference for all consumers with $v \geq p_1$ and argued that the indifference facilitates implementation of the investment project. For $T \neq T^*$ this is no longer the case as reaching the target level in this case would imply a price change.[55] In fact one can interpret the choice $T = T^*$ as a commitment device as outlined in the following result.

[53] This argument is also applicable to the equilibrium outcome presented in section 3.4.2

[54] A setup with sequential arrival of consumers is also presented e.g. in Alaei et al. (2016) and Strausz (2017). The difference to our sequentiality setting is that we make an assumption on the order of arrival, whereas the previously mentioned papers consider i.i.d. draws. The motivation behind this setup is discussed in section 3.5.2 in more detail.

[55] For $T \neq T^*$ the equilibrium reasoning from section 3.4.2 can be applied.

Proposition 3.3 *By setting $T = T^*$, E can pre-commit to not change prices in case of a successful crowdfunding campaign.*

This eliminates the price risk faced by consumers. In case the demand state is too low, there is no risk in pledging due to the all-or-nothing property such that all pledges are refunded. In case the demand state is sufficiently high, the target will be precisely met such that it is sequentially rational for E not to change prices. We can now analyze T^* as function of p_1 in more detail.

Lemma 3.3 *The equilibrium target level $T^*(p_1)$ satisfies $T^*(0) = T^*(p^M) = 0$ and $T^*(p_1) > 0$ for $p_1 \in (0, p^M)$.*

Proof. See Appendix. □

To gain intuition for this result recall how T^* was constructed. The target level T^* is chosen in a way that E finds it optimal to subsequently not change prices. E would pick $p_2 = p^M$ if the entire support of valuations is still available, hence $T^*(p^M) = 0$ with $\underline{s} = 0$. Similarly, for $p_1 = 0$ we have the degenerate case of $T^*(0) = 0$ but $\underline{s} = 1$ such that there is no state where period 2 is reached, hence $p_2 = 0$ would be optimal as well. For intermediate values $p_1 \in (0, p^M)$ we have $T^*(p_1) > 0$ and $\underline{s} \in (0, 1)$. The actual choice of p_1 and hence $T^*(p_1)$ is determined by the financing needs of the entrepreneur. To see this note that given the established results we can denote period 1 profits as

$$\Pi_1(p_1|s) = \begin{cases} T^* - I & \text{if } s \geq \underline{s} \\ 0 & \text{else.} \end{cases} \tag{3.29}$$

Using $p_2 = p_2^*(p_1, T^*) = p_1$ we obtain after rearranging $\mathbb{E}[\Pi_2(p_2|s, p_1)|T^*] = \mathbb{E}[s|s \geq \underline{s}]p_1(1 - G(p_1)) - T^*$ with $\mathbb{E}[s|s \geq \underline{s}] = (1 + \underline{s})/2$, such that we can write the ex-ante retail profits as

$$\Pi_2(p_1|s) = \begin{cases} \mathbb{E}[s|s \geq \underline{s}]p_1(1 - G(p_1)) - T^*(p_1) & \text{if } s \geq \underline{s} \\ 0 & \text{else.} \end{cases} \tag{3.30}$$

The ex-ante profit maximization problem is then given by

$$\begin{aligned}
\max_{p_1} \mathbb{E}\left[\Pi_1(p_1|s) + \Pi_2(p_1|s)\right] &= \max_{p_1} \int_0^1 \left[\Pi_1(p_1|s) + \Pi_2(p_1|s)\right] f(s)ds \\
&= \max_{p_1} \int_{\underline{s}}^1 \left[\Pi_1(p_1|s) + \Pi_2(p_1|s)\right] f(s)ds \\
&= \max_{p_1} \int_{\underline{s}}^1 \left[\mathbb{E}[s|s \geq \underline{s}]p_1(1-G(p_1)) - I\right] ds \\
&= \max_{p_1} \underbrace{(1-F(\underline{s}))}_{\text{Success probability}} \underbrace{[\mathbb{E}[s|s \geq \underline{s}]p_1(1-G(p_1)) - I]}_{\text{Expected profit in case of success}} \\
&\text{s.t. } T^*(p_1) \geq I
\end{aligned} \tag{3.31}$$

To see that the constraint is binding note that the target function is increasing on $p_1 \in (0, p^M)$ such that (ignoring the feasibility constraint) expected profit is maximized for the monopoly price.[56] Recalling Lemma 3.3 we see $T^*(p^M) = 0$, as the only target level which would make it subsequently optimal to pick the monopoly price, is precisely a total demand of zero in period 1, such that E would face the one-shot monopoly problem in period 2. Obviously, this violates feasibility for any $I > 0$ such that the constraint must be binding.

3.5 Discussion and robustness

We characterized two equilibrium outcomes satisfying the stability condition. The uncoordinated equilibrium allows for arbitrary target levels and guarantees price stability whenever the CF campaign is successful. The coordinated equilibrium requires $T = T^*$ and also guarantees price stability. In the uncoordinated equilibrium the entrepreneur perfectly learns the demand state s, making the period 2 maximization problem deterministic. As the optimal retail price does not depend on the demand state but only on the cutoff valuation, an appropriately chosen cutoff valuation eliminates the price risk faced by consumers. In the coordinated equilibrium E learns the demand state imperfectly, as observing a pledge level T^* is consistent with multiple demand states. However, T^* is chosen in a way, that the retail price which maximizes expected profits conditional on observing T^* is precisely equal to p_1. Figure 3.4 depicts simulated outcomes for both equilibrium types.

Comparing the coordinated outcome to the data illustrated in figure 3.1 we see the occurrence of the clustering of pledge levels at the target level, while the uncoordinated outcome shows a random distribution of total pledge levels. In the following we would like to discuss which aspects might favor one equilibrium type over the other and thereby also discuss robustness of our results.

[56] We refer to Appendix 3.A.1 for detailed derivations.

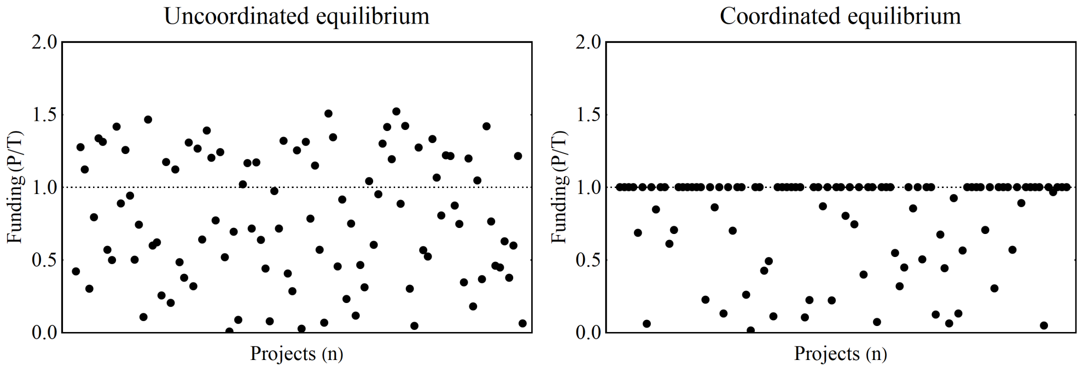

FIGURE 3.4: Simulated equilibrium outcomes

Both figures depict equilibrium total pledge levels $P(p_1^*|s)$ for $n = 100$ draws of the demand state s. The project size is held constant $I = 0.08$ and the distribution of valuations is assumed to be uniform such that $G(v) = v$ and $g(v) = 1$.

3.5.1 Efficiency

Note that even though the two equilibrium outcomes differ in terms of price and demand dynamics, they share some efficiency properties. First of all, it is straightforward to see that both equilibrium outcomes satisfy ex-post efficiency in the sense that they allow to screen for demand states where it is ex-post efficient to make the investment. This characteristic follows directly from the AoN property of the CF mechanism, as it allows E to condition the investment decision on states of the world where demand is proven to be high enough to cover investment costs. This property is often seen as one of the major advantages of CF compared to other funding sources. It is also easy to see that while both outcomes guarantee ex-post efficiency, they are both not first-best allocations. A first best mechanism would implement the project whenever consumer valuations are sufficiently high, which is the case in states $s \in S_{FB}$ where

$$S_{FB} = \left\{ s \in S \,\middle|\, s \int_{v \in V} v g(v) dv \geq I \right\}. \tag{3.32}$$

Note that this is clearly not attainable as we restrict the model to uniform prices. Constraining the efficiency benchmark to uniform prices yields the second-best (or constrained first-best) set of states

$$S_{SB} = \left\{ s \in S \,\middle|\, s p^M (1 - G(p^M)) \geq I \right\}. \tag{3.33}$$

Note that $S_{SB} \subset S_{FB}$ and that p^M is revenue maximizing irrespective of the demand state. S_{SB} is therefore the largest subset of S_{FB}, attainable by uniform prices. Our analysis showed however, that equilibrium prices will be below p^M, which implies that the presented equilibrium outcomes also come at a cost compared to the second best. In a sense, this is an implication of the Coase conjecture (Coase, 1972). If the good is durable, the sequential monopolist competes against its future self, which limits the ability to raise prices in period 1. One way to overcome this ‘inefficiency’ would be price commitment. If E could credibly commit to period 2 prices, second best is attainable by setting $p_1 = p^M$, $p_2 > p^M$ and $T = I$. However, it is unclear to what extent entrepreneurs can credibly commit to retail prices throughout a CF campaign. We would therefore like to stress that while the characterized equilibrium outcomes are not optimal from an efficiency perspective, they still exhibit a screening property (see e.g. Strausz, 2017), such that any investment decision made is ex-post efficient.

3.5.2 Sequential pledging

In this section we consider an alternative timing to the game structure. Remember the campaign length spans $t = [0, 1]$, starting with the decision on ψ at $t = 0$ and running up to $t = 1$. Now assume that consumers arrive sequentially in descending order of valuation throughout the campaign length.

Assumption 3.2 (Sequential arrival) *At time $t \in [0, 1]$ consumers with valuation $v = 1 - t$ enter the market and become aware of the CF campaign.*

The idea behind this assumption is that not all consumers decide simultaneously whether to participate in the CF or not. Typically, consumers become aware of a CF campaign, read the project's description, observe the current pledge level, and then decide whether to pledge or not. Crucially, the assumption prescribes that consumers with high valuations make their decision before consumers with low valuations. This might be the case if e.g. consumers with very high valuation for a product type (e.g. board games) actively search among ongoing CF campaigns for new products (e.g. innovative board game concepts), whereas consumers with low valuations might stumble upon the CF campaign throughout time. Alternatively, high valuation consumers might be active in online communities (e.g. board game forums) where the CF campaign was announced prior to the start, potentially even by E herself, while low valuation consumers were not aware of the announcement, and therefore become aware of the campaign at a later stage.

This changes the game to the extent that now consumers observe the current total pledge level at the time they enter the market which we denote by P_t.[57] Consumers will therefore update their prior belief about demand states to a set $\hat{S}_v$ which contains demand states consistent with observing P_t. The uncoordinated equilibrium is robust to the sequential arrival of consumers as the decision whether to pledge or not just depends on the consumers' valuation v. However, we now verify that the characterized coordinated equilibrium arises naturally as an uncoordinated equilibrium.

To see this note that the state dependent cutoff valuations presented in section 3.4.3 arise naturally if $T = T^*$ and if consumers follow a simple decision rule: pledge if $P_t < T^*$ and $v \geq p_1$. The decision rule therefore prescribes consumers to pledge

[57] Note the equivalence of $v = 1 - t$ in this setting, such that indices t and v are interchangeable where it does not lead to confusion.

only if their valuation is sufficiently high and the target level has not been reached. The evolution of the total pledge level in different demand states throughout the CF period is depicted in figure 3.5.

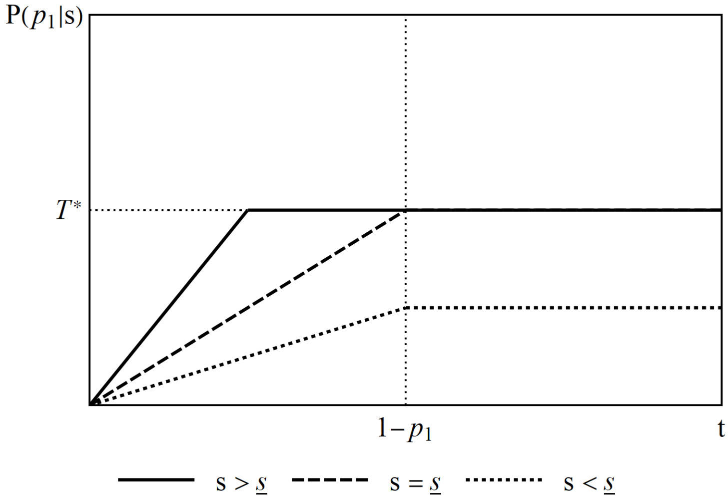

FIGURE 3.5: Sequential pledging

If the demand state is high ($s > \underline{s}$) the target is reached quickly, while $s = \underline{s}$ denotes the last demand state where the target is eventually reached. If the demand state is low ($s < \underline{s}$), the CF campaign entirely fails to reach the target level. We can now verify that following this sequential pledging strategy is indeed optimal.

Starting with consumers $v < p_1$ the pledging strategy prescribes to wait, which is trivially satisfied. For $v \geq p_1$ we have to distinguish two cases. Let us start with the case $v \geq p_1$ and $P_t = T^*$. In this case it must be optimal for consumers to wait according to the decision rule. This implies that the target has been reached at some cutoff valuation $\overline{v}(p_1|s)$ above v such that $\hat{S}_v = \{s \in S | \overline{v}(p_1|s) > v\}$. As in this case consumers know for sure that the CF campaign is successful and that prices remain unchanged as long as the total pledge level does not rise above T^*, consumers have no incentive to pledge, i.e. waiting is optimal.

Let us now consider $P_t < T^*$ and $v \geq p_1$ where the decision rule requires that it is optimal to pledge. As the target has not been reached yet, it implies that the current pledge level is the result of all consumers with valuations higher than v pledging such that $\hat{S}_v = \{s \in S | sp_1 \int_v^1 g(w)dw = P_t\}$. Note that this is a singleton set which includes only the true demand state. But then it is optimal to pledge as either $s \in \underline{S}$ such that consumers know that the CF campaign is going to be successful (and future consumers will stop pledging once T^* has been reached), or $s \notin S$ which implies that consumers know that the campaign will fail, but due to the AoN property consumers have nothing to lose from pledging. In both cases pledging is therefore optimal. Hence, following the simple decision rule mentioned above is optimal which gives rise to the state dependent cutoff valuations from section 3.4.3.[58]

3.5.3 Moral hazard

So far we assumed that whenever E obtains sufficient funds to cover investment costs, the investment is made. Now suppose that whenever E obtains a transfer P, she can embezzle the transferred money instead of making the investment and keep a fraction $\alpha \in [0,1]$ of it. The parameter α then measures the extent of moral hazard, where a low α implies that it is very costly to embezzle funds (e.g. high reputation or legal costs), while a high α corresponds to a 'wild west' scenario, where there are basically no repercussions in case of fraud. This setup resembles the moral hazard problem in Strausz (2017).

Starting with the uncoordinated outcome we obtain the interim moral hazard constraint

$$P(p_1|s) - I + \Pi_2(p_1|s) \geq \alpha P(p_1|s). \tag{3.34}$$

Note that whether or not this constraint is satisfied, may depend on the realization of the demand state s. In particular, the constraint might be satisfied for very high states but be violated in low demand states if α is sufficiently large. To see this consider the lowest success state $\underline{s}$. As $T = I$ in optimum, we obtain $P(p_1|\underline{s}) = T = I$ such that the constraint reduces to $\Pi_2(p_1|\underline{s}) \geq \alpha I$. If the constraint is satisfied for $\underline{s}$, then it is also satisfied for $s > \underline{s}$, as the LHS of (3.34) grows faster than the RHS (recall that $P(p_1|s)$ and $\Pi_2(p_1|s)$ are linear in s in the uncoordinated case). In this case the presented analysis is valid and the outcome is robust to moral hazard. However, for large α or I it is also possible that the constraint is violated for $s = \underline{s}$ but satisfied for some high demand states $s > \underline{s}$. In this case the presented analysis is no longer valid, as consumers would face uncertainty about whether or not E will embezzle the funds and are therefore no longer indifferent between pledging and waiting.

In the coordinated outcome we obtain the interim moral hazard constraint $T^* - I + \mathbb{E}[\Pi_2(p_1|s)|s \geq \underline{s}] \geq \alpha T^*$. Recalling that $T^* = I$ is binding in the optimum, we can simplify the constraint to

$$\mathbb{E}[\Pi_2(p_1|s)|s \geq \underline{s}] \geq \alpha T^*. \tag{3.35}$$

The constraint is very intuitive as it requires that expected sales from the retail stage must exceed the payoff from running away. Hence, by limiting demand during the CF campaign to T^* and deferring payments to the retail stage, the moral hazard problem

[58]Note that the sequential pledging is sub-game perfect, i.e. even if some consumers who were supposed to pledge refrained from pledging, it is still optimal to pledge and 'to fill the funding gap' as long as $v \geq p_1$. The reason is that in this case only the success probability of the CF campaign decreases while the mechanism behind Lemma 3.2 still applies. Also, there is nothing to gain by pledging once the target has been reached. Hence, the sequential pledging strategy is sub-game perfect.

can be overcome (see Strausz, 2017), at least for low levels of α. The constraint becomes more difficult to satisfy for large α and I. For large I the transfer T^* to E also needs to be high in order to cover investment costs. This reduces the expected payoff from retail sales, as a large chunk of demand is already served, while making the outside option of running away with the money very attractive. The characterized equilibrium outcome is therefore robust to moral hazard as long as the moral hazard problem is not too severe.

3.5.4 Uncertain distribution of valuations

So far we considered the case of uncertainty regarding the total market size. One important implication of this setup was that the distribution of valuations is independent of the demand state. In the following we want to discuss how changes to this assumption affect our results.

Consider a fixed total market size $M = 1$ with state dependent distribution of valuations $G(v|s)$ and $g(v|s) = \partial G(v|s)/\partial v > 0 \ \forall \ v \in V, s \in S$ where the demand state s orders the family of distributions $G(v|s)$ in the spirit of first-order stochastic dominance (FOSD), such that for two demand states $s_1, s_2 \in S$ with $s_1 > s_2$ we have $G(v|s_1) \leq G(v|s_2) \ \forall \ v \in V$. Now the demand state does not affect the total market size any longer, but rather specifies to what extent consumers have high-valuations for the product. A high demand state therefore indicates that high-valuations are more common than in a low demand state. Before we characterize the equilibrium conditions, we need to introduce an assumption which extends the concept of the monotone hazard rate to this setting.

Assumption 3.3 (Regularity) *The distribution $G(v|s)$ is twice continuously differentiable in v and s and exhibits*

1. $\partial H(v|s)/\partial v < 0$ *for all* $v \in V, s \in S$ *with* $H(v|s) := \frac{1-G(v|s)}{g(v|s)}$,
2. $\partial \tilde{H}(v|s \geq c)/\partial v < 0$ *for all* $v \in V$ *and* $s, c \in S$ *with* $\tilde{H}(v|s \geq c) := \frac{E[1-G(v|s)|s \geq c]}{E[g(v|s)|s \geq c]}$.

This assumption is necessary to assure uniqueness of the optimal retail price. Also, let $\tilde{p}^M$ therefore denote the one-shot revenue maximizing price which is implicitly defined by $\tilde{p}^M = \tilde{H}\left(\tilde{p}^M|s \geq 0\right)$. Note that the idea behind Lemma 3.1 must still hold such that we can again implicitly assume $p_1 < \tilde{p}^M$, while we discuss in the following to what extent the stability condition can still hold. Note that now prior consumer beliefs about the demand state depend on their valuation v, as $f(s|v) = g(v|s)f(s)/\left(\int_{s\in S} g(v|s)f(s)ds\right)$. However, in case there is a demand schedule satisfying the stability condition, consumers with $v \geq p_1$ are still indifferent between pledging and waiting, as the heterogeneity in consumer beliefs only affects the success probability of the campaign, while anticipated retail prices are still equal to p_1 in each success state.

Uncoordinated equilibrium

It is easy to verify that the uncoordinated outcome can no longer yield stable prices. Suppose there exists an equilibrium where consumers follow a cutoff strategy, such that they pledge if $v \geq \overline{v}(p_1)$ and wait otherwise, as in section 3.4.2. If such an equilibrium exists, then observing a successful CF campaign is again perfectly informative (see section 3.4.2). This gives to rise to an optimal retail price $p_2^*(\overline{v}(p_1)|s)$ which is implicitly defined by

$$p_2^* = \frac{G(\overline{v}(p_1)|s) - G(p_2^*|s)}{g(p_2^*|s)} \tag{3.36}$$

and is unique under Assumption 3.3.1. We immediately see that while the optimal retail price $p_2^*(\overline{v}(p_1)|s)$ is monotone in $\overline{v}(p_1)$, it now depends on the demand state s. This implies that if such an equilibrium exists, retail prices may fluctuate depending on the outcome of the CF campaign. Hence, the stability condition can no longer hold.

Coordinated equilibrium

While we can not provide close-form solutions of the 'coordination target level' $T^*(p_1)$, we can nevertheless prove existence. For this we define state dependent cutoff valuations $\overline{v}(p_1|s)$ just as before, such that whenever the demand state permits the target level T^* is reached.

Now suppose E observes a total pledge level of T^* resulting in an updated set of states $\hat{S} = \underline{S} \equiv [\underline{s}, 1]$ where $\underline{s} : T = p_1(1 - G(p_1|\underline{s}))$.[59] This results in an optimal retail price $p_2^*(p_1, T^*)$ which is implicitly defined by

$$p_2^* = \frac{\mathbb{E}\left[G(\overline{v}(p_1|s)|s) - G(p_2^*|s)|s \geq \underline{s}\right]}{\mathbb{E}\left[g(p_2^*|s)|s \geq \underline{s}\right]} \tag{3.37}$$

which is unique under Assumption 3.3.2. We can now ask the same question as before: is there a level T^* such that it is sequentially rational for E not to change prices? For $T^* = \underline{T} \equiv 0$ the entrepreneur would choose $p_2^* = \tilde{p}^M > p_1$, while for the largest possible T^* where even in the highest demand all consumers with $v \geq p_1$ would have to pledge, i.e. $T^* = \overline{T} \equiv p_1(1 - G(p_1|1))$, we would clearly obtain $p_2^* < p_1$. But then we know from the intermediate value theorem that there exists some $T^* \in (\underline{T}, \overline{T})$ such that $p_2^*(p_1, T^*) = p_1 \ \forall \ s \in \underline{S}$, which satisfies the stability condition outlined in Proposition 3.2. Hence, the coordinated equilibrium exists if we consider uncertainty regarding consumer valuations.

[59] The compactness of $\underline{S}$ follows from the FOSD property.

3.5.5 Proportional rationing

The two presented equilibrium outcomes prescribe in case of indifference that consumers with high valuations pledge instead of consumers with lower valuations. We motivated this by drawing the analogy to the concept of efficient rationing. In the following we demonstrate that in fact there can not exist price-stable equilibria if we apply the alternative concept of 'proportional rationing', i.e. where all consumers with $v \geq p_1$ pledge with a certain probability.

Uncoordinated equilibrium

Starting with the uncoordinated equilibrium we demonstrate that the stability condition can not be satisfied if all consumers with $v \geq p_1$ mix with some probability $\beta \in (0,1)$. Suppose there is such an equilibrium. Then observing a certain pledge level is again perfectly informative as $P = sp_1 \int_{p_1}^1 \beta g(v)dv = sp_1\beta(1 - G(p_1))$. The residual demand in the retail period is then given by

$$D_2(p_2|s,p_1) = \begin{cases} s\,(1 - \beta(1 - G(p_1)) - G(p_2)) & \text{if } p_2 < p_1 \\ s(1-\beta)(1 - G(p_2)) & \text{else} \end{cases} \tag{3.38}$$

such that marginal retail profits are given by

$$\Pi_2'(p_2|s.p_1) = \begin{cases} s\,[1 - \beta(1 - G(p_1)) - G(p_2) - p_2 g(p_2)] & \text{if } p_2 < p_1 \\ s\,[(1-\beta)\,(1 - G(p_2)) - (1-\beta)\,p_2 g(p_2)] & \text{if } p_2 > p_1 \end{cases} \tag{3.39}$$

while marginal profits are not defined for $p_2 = p_1$. A solution candidate β^* would therefore be given if the maximal retail profit is precisely reached in the 'kink' at $p_2 = p_1$ in order to satisfy the stability condition. If there exists such a β^* then marginal profits have to be positive left of the kink

$$\lim_{p_2 \to p_1^-} \Pi_2'(p_2|s,p_1) = s\,[1 - \beta^*(1 - G(p_1)) - G(p_1) - p_1 g(p_1)] > 0$$
$$\Leftrightarrow (1-\beta^*)H(p_1) > p_1 \tag{3.40}$$

and negative right of the kink

$$\lim_{p_2 \to p_1^+} \Pi_2'(p_2|s,p_1) = s\,[(1-\beta^*)\,(1 - G(p_1)) - (1-\beta^*)\,p_1 g(p_1)] > 0$$
$$\Leftrightarrow H(p_1) < p_1. \tag{3.41}$$

It is easy to see that the first condition can be satisfied for low values of $\beta < \overline{\beta} \equiv 1 - p_1/H(p_1)$ while the second condition is violated for all $p_1 < p^M$. In combination with Lemma 3.1 this implies that there can not be an equilibrium where all consumers mix with a probability $\beta \in (0,1)$. This is depicted in the following graph where we illustrate the retail profit maximization problem for varying levels of β.

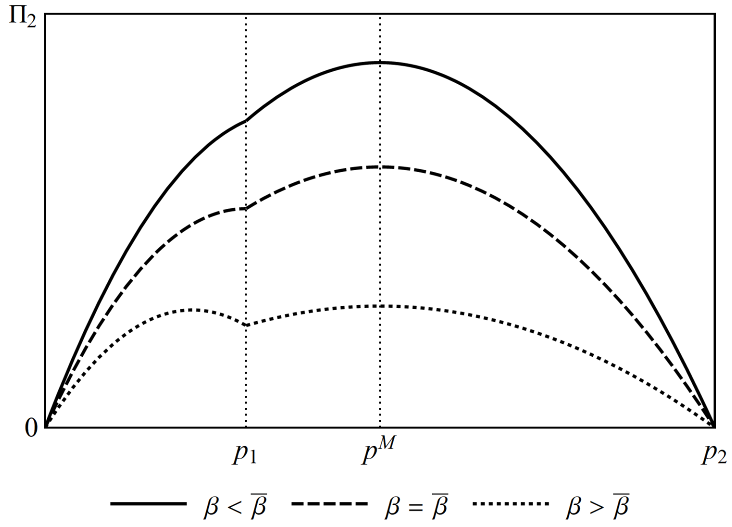

FIGURE 3.6: Retail profits under a proportional rationing rule

We immediately see that the incentive to decrease prices below p_1 is given as long as $\beta > \overline{\beta}$. For $\beta \geq \overline{\beta}$ this incentive disappears. However, we see that there is always an incentive to increase prices above p_1, irrespective of the level of β. In fact one can see the link to the previous analysis if we consider the case $p_1 = p^M$. Then $\beta = 0$ would yield $p_2^* = p^M$, i.e. price stability. However, $\beta = 0$ implies that no consumer pledged in the CF period.

Coordinated equilibrium

In the coordinated case we allow the rationing probability to be state dependent. In particular let $\beta(s)$ be the pledging probability necessary to reach a target level T such that $T = sp_1\beta(1 - G(p_1))$ for all $s \geq \underline{s}$ where $\underline{s} = T/(p_1(1 - G(p_1)))$ with $\beta(\underline{s}) = 1$ and

$$\beta(s) = \frac{T}{sp_1(1 - G(p_1))} < 1 \tag{3.42}$$

for $s > \underline{s}$. The resulting period 2 demand is then given by

$$D_2(p_2|s, p_1) = \begin{cases} s\left(1 - \beta(s)(1 - G(p_1)) - G(p_2)\right) & \text{if } p_2 < p_1 \\ s\left(1 - \beta(s)\right)\left(1 - G(p_2)\right) & \text{else} \end{cases} \tag{3.43}$$

or equivalently

$$D_2(p_2|s, p_1) = \begin{cases} s\left(1 - \frac{T}{sp_1} - G(p_2)\right) & \text{if } p_2 < p_1 \\ s\left(s - \underline{s}\right)\left(1 - G(p_2)\right) & \text{else} \end{cases}. \tag{3.44}$$

It is straightforward to verify that the maximization problem $\max_{p_2} \mathbb{E}[\Pi_2(p_2|s, p_1)|s \geq \underline{s}] = \max_{p_2} \int_{\underline{s}}^1 p_2 D(p_2|s, p_1)\underline{f}(s)ds$ is continuous but differentiable only for $p_2 \neq p_1$.

Nevertheless we can take a look at the marginal profits for $p_2 > p_1$ which are given by

$$\frac{\partial \mathbb{E}[\Pi_2(p_2|s,p_1)|s \geq \underline{s}]}{\partial p_2} = \int_{\underline{s}}^{1} (s-\underline{s})\left(1-G(p_2)-p_2 g(p_2)\right)\underline{f}(s)ds. \tag{3.45}$$

Keeping in mind that Lemma 3.1 still holds such that $p_1 < p^M$, we immediately see that marginal profits are positive for $p_2 \in (p_1, p^M)$. The entrepreneur would therefore have an incentive to increase prices above p_1 for any $p_1 < p^M$ and any T.[60] This implies that the stability condition can not be satisfied if we consider coordination with respect to a proportional rationing probability and therefore there can not exist an equilibrium if we apply the proportional rationing rule in this context.

3.6 Conclusion

We characterized equilibrium outcomes in a setting where a monopolist entrepreneur raises funds through pre-selling her product in an all-or-nothing CF campaign, before offering her product on a retail market to all remaining consumers. In order to overcome the price risk faced by consumers, demand spreads across the CF and the retail period in a way such that the entrepreneur finds it optimal to leave prices unchanged once the CF is successfully completed. This is done by consumers with high valuations pledging in the CF campaign, while consumers with low valuations wait for the retail sales.

In particular, we characterized an equilibrium, where in light of demand uncertainty, the funding target is reached whenever possible, but consumer demand never exceeds the funding target, inducing the entrepreneur to leave prices unchanged. The target level in this case acts as device to pre-commit not to change prices, eliminating the price risk faced by consumers. This pledging pattern is consistent with empirical observations where we observe that CF campaigns which are successful, are usually successful only by a small margin, leading to a clustering of total pledge levels around the target level.

We perform a variety of robustness checks to the presented equilibrium outcomes and demonstrate that the characterized pledging pattern is robust to changes in the timing of consumer arrival, the way how we model demand uncertainty, and moral hazard, as long as the moral hazard problem is not too severe.

However, our model only explains certain aspects of the stylized facts of observed funding patterns. The funding outcome of CF campaigns tends be bimodal with a clustering of the funding ratio P/T around 1 and 0. While our model does provide an explanation for the clustering around $P/T = 1$, it remains silent why only relatively few projects fail with a funding rate close to one. Here, a richer model incorporating

[60] To see this rearrange $1 - G(p_2) - p_2 g(p_2) > 0$ to $H(p_2) > p_2$ which is satisfied for all $p_2 < p^M$.

an entrepreneur who is not completely money-less could provide additional insights, as the entrepreneur could then bridge the funding gap if the CF campaign is at risk to fail by a close margin.

Also, we focus on equilibria exhibiting price stability. It would be interesting to further explore whether, and to what extent, price fluctuations may arise in a CF setting. This might be particularly interesting in a setting where the distribution of valuations depends on the demand state, as suggested in section 3.5.4.

Lastly, it would also be interesting to investigate the intertemporal price dynamics of CF campaigns with subsequent retail sales empirically. As a large share of successful CF campaigns continues to operate as independent ventures after the CF has been completed (see Mollick and Kuppuswamy, 2014), linking the price data to the CF campaign might yield valuable insights.

3.A Appendix

3.A.1 Omitted analysis

Ancillary results

The following Lemma introduces a technical result which is used throughout the remaining analysis.

Lemma 3.4 *For $\chi(v) := G(v) + vg(v)$ it holds $\chi'(v) = 2g(v) + vg'(v) > 0$ for all $v < p^M$.*

Proof. For $g'(v) \geq 0$ the inequality is trivially satisfied. For $g'(v) < 0$ we know from Assumption 3.1 $H'(v) < 0$ or equivalently $g'(v) > -g(v)^2/(1 - G(v))$. Replacing $g'(v) = -g(v)^2/(1 - G(v))$ in $\chi'(v) > 0$ and rearranging yields $H(v) > v/2$ which is satisfied for all $v < p^M$. $\square$

Coordinated equilibrium

In the following we demonstrate that the target function of the ex-ante profit maximization problem in (3.31) is increasing in p_1. We start by introducing the following interim result.

Lemma 3.5 *Let $T = T^*(p_1)$. The minimal success state $\underline{s} = T^*(p_1)/(p_1(1 - G(p_1)))$ is decreasing in p_1 for $p_1 \in (0, p^M)$ such that $d\underline{s}/dp_1 < 0$.*

Proof. First note that $d\underline{s}/dp_1 < 0$ reduces to $-(1 - G(p_1))\,(g(p_1) + p_1 g'(p_1)) < p_1 g(p_1)^2$ which is trivially satisfied for $g'(p_1) \geq 0$ as we then have $LHS < 0$ and $RHS > 0$. For $g'(p_1) < 0$ we can rearrange the inequality to $g(p_1)/p_1 + g'(p_1) > -g(p_1)/H(p_1)$. From Assumption 3.1 we have $H'(v) < 0$ or equivalently $g'(v) > -g(v)/H(v)$ for all $v \in V$. Hence, the inequality is satisfied for $g'(p_1) < 0$ as well, concluding this proof. $\square$

The profit maximization problem $\max_{p_1} \mathbb{E}[\Pi_1(p_1|s) + \Pi_2(p_1|s)]$ s.t. $T^*(p_1) \geq I$ yields after simplification

$$\max_{p_1} (1 - \underline{s}) \left[\frac{1}{2}(1 + \underline{s}) p_1 (1 - G(p_1)) - I\right] \text{ s.t. } T^*(p_1) \geq I. \tag{3.46}$$

Focusing on the target function we obtain after differentiating with respect to p_1 and basic simplifications

$$\frac{d\mathbb{E}[\Pi_1 + \Pi_2]}{dp_1} = \frac{d\underline{s}}{dp_1}\left[-\underline{s} p_1 (1 - G(p_1)) + I\right] + \frac{1}{2}(1 - \underline{s}^2)(1 - G(p_1) - p_1 g(p_1)) > 0. \tag{3.47}$$

To see why the inequality holds note that $-\underline{s}p_1(1-G(p_1))+I \leq 0$ can be rearranged to $I \leq \underline{s}p_1(1-G(p_1))$ or equivalently $I \leq T^*(p_1)$, which is the feasibility constraint. Also, we know $d\underline{s}/dp_1 < 0$ from Lemma 3.5 while $\frac{1}{2}(1-\underline{s}^2)(1-G(p_1)-p_1g(p_1)) > 0$ for $p_1 < p^M$. Hence, the target function of the maximization problem in (3.31) is increasing in p_1.

3.A.2 Omitted proofs

Proof of Lemma 3.1

Proof. Implementation of the investment project requires positive demand in period 1 which implies that some consumers with valuation $v \geq p^M$ have left the market in period 2, hence the profit maximizing period 2 price will be strictly below p^M for any positive demand in period 1. Hence, individual consumers would be better off to wait instead of pledging. □

Proof of Lemma 3.2

Proof. It turns out to be helpful to rewrite the maximization problem in (3.24) using a piecewise-defined integral bound instead of the piecewise-defined integrand given by the residual demand function $D_2(p_2|s)$. We therefore consider the equivalent maximization problem

$$\mathbb{E}\left[\Pi_2(p_2|s)|T\right] = \mathbb{E}\left[\Pi_2(p_2|s)|s \geq \underline{s}\right] = \int_{z(p_2)}^{1} s\left[G(\overline{v}(p_1|s) - G(p_2)\right]\underline{f}(s)ds \qquad (3.48)$$

where

$$z(p_2) = \begin{cases} \underline{s} & \text{if } p_2 \leq p_1 \\ \frac{T}{p_1(1-G(p_2))} & \text{if } p_1 < p_2 \leq \overline{p}_2 \\ 1 & \text{if } p_2 > \overline{p}_2 \end{cases} \qquad (3.49)$$

such that for $p_2 \leq p_1$ we obtain the original maximization problem as in (3.24) while for $p_1 < p_2$ we take into account the piecewise definition of $D_2(p_2|s)$ by shifting the lower integration bound upwards. The expression $T/\left(p_1(1-G(p_2))\right)$ is therefore obtained by solving for the state z satisfying $G(\overline{v}(p_1|z)) - G(p_2) = 0$. Lastly, we need to specify an upper bound such that even in the highest possible state ($s = 1$) no consumers would be left to purchase the good, which is given by $G(\overline{v}(p_1|1)) - G(\overline{p}_2) = 0$, or equivalently $z(\overline{p}_2) = 1$.

Applying Leibniz's rule for differentiation to the maximization problem in (3.48) yields after rearranging the first order condition

$$p_2^* = \frac{\mathbb{E}\left[s\left(G(\overline{v}(p_1|s)) - G(p_2^*)\right)|s \geq z(p_2^*)\right]}{\mathbb{E}\left[sg(p_2^*)|s \geq z(p_2^*)\right]} \qquad (3.50)$$

which implicitly defines the profit maximizing retail price p_2^*. Note that (3.50) can be rewritten after basic simplification steps as

$$p_2^* = \frac{G(\overline{v}(p_1|\tilde{z}(p_2^*))) - G(p_2^*)}{g(p_2^*)} \tag{3.51}$$

where $\tilde{z}(p_2) = \mathbb{E}[s|s \geq z(p_2)] = (1+z(p_2))/2$. To prove that the solution p_2^* to (3.51) is unique, we show that the RHS of (3.51) is strictly decreasing in p_2. To ease notation we define $l(p_2) := G(\overline{v}(p_1|\tilde{z}(p_2))) = 1 - T/(p_1\tilde{z}(p_2))$ such that $dRHS/dp_2 < 0$ is satisfied if

$$g(p_2)(l'(p_2) - g(p_2)) - (l(p_2) - G(p_2))g'(p_2) < 0. \tag{3.52}$$

As $l'(p_2) = 2\left[T/\left((p_1(1 - G(p_2)) + T\right)\right]^2 g(p_2)$ we can rewrite (3.52) as

$$-g(p_2)^2\xi - (l(p_2) - G(p_2))g'(p_2) < 0 \tag{3.53}$$

where $\xi = 1 - 2(T/(p_1(1 - G(p_2)) + T)^2$ with $\xi \in (0, 1)$.[61] For $g'(p_2) \geq 0$ the condition is trivially satisfied as $\xi > 0$ as well as $l(p_2) - G(p_2) > 0$ for $p_2 < \overline{p}_2$. For $g'(p_2) < 0$ we obtain a lower bound on $g'(p_2)$ from Assumption 3.1 as $H'(v) < 0$ implies $-g(v)^2/(1 - G(v)) < g'(v)\ \forall v \in V$. Evaluating (3.53) at the lower bound reduces to $0 < 1 - T/(T + p_1(1 - G(p_2)))$, which is true. Therefore, (3.53) is satisfied also for $g'(p_2) < 0$ which implies that the RHS of (3.51) (or equivalently (3.52)) is strictly decreasing. Hence, the profit maximizing retail price is unique and satisfies $p_2^* \in (0, \overline{p}_2)$. Substituting $T = T^*$ into the FOC then yields after rearranging

$$G(p_2^*) + p_2^* g(p_2^*) = G(p_1) + p_1 g(p_1). \tag{3.54}$$

From Lemma 3.4 we know that $\chi(v) = G(v) + vg(v)$ is a monotone function for $v < p^M$ such that (3.54) is satisfied only for $p_2^* = p_1$, which implies $p_2^*(p_1, T^*) = p_1$. To prove the inequalities in Lemma 3.2 we show that $dp_2^*/dT|_{T=T^*} < 0$. We obtain dp_2^*/dT from totally differentiating the LHS and RHS in (3.50) with respect to T such that

$$\frac{dp_2^*}{dT} = \frac{\partial RHS/\partial T}{1 - \partial RHS/\partial p_2} \tag{3.55}$$

which yields after substituting $T = T^*$ (and hence $p_2 = p_1$)

$$\left.\frac{dp_2^*}{dT}\right|_{T=T^*} = -\frac{(1 - G(p_1) + p_1 g(p_1))^2}{2p_1(1 - G(p_1))^2(2g(p_1) + p_1 g'(p_1))}. \tag{3.56}$$

Note that we have $(2g(p_1) + p_1 g'(p_1)) > 0$ by Lemma 3.4 such that $dp_2^*/dT|_{T=T^*} < 0$. □

[61] To see this note that $\xi > 0$ reduces to $z(p_2) < 1/(\sqrt{2} - 1)$ which is satisfied as $z(p_2) \leq 1$.

Proof of Lemma 3.3

Proof. We immediately see that for $p_1 = 0$ one factor of T^* becomes zero. For $p_1 = p^M$ we can take a look at the numerator of the fraction $(1 - G(p_1) - p_1 g(p_1))/(1 - G(p_1) + p_1 g(p_1))$, while the denominator is positive for all p_1. To see that $1 - G(p^M) - p^M g(p^M) = 0$ rearrange the terms to $H(p^M) = p^M$ which is the definition of p^M. For intermediate values of p_1 the numerator is positive (as $p_1 < H(p_1)$) while the denominator is always positive, resulting in $T^* > 0$ for $p_1 \in (0, p^M)$. $\square$

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Selbständigkeitserklärung

Ich bezeuge durch meine Unterschrift, dass meine Angaben über die bei der Abfassung meiner Dissertation benutzten Hilfsmittel, über die mir zuteil gewordene Hilfe sowie über frühere Begutachtungen meiner Dissertation in jeder Hinsicht der Wahrheit entsprechen.

Berlin, 07.09.2018

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